/JERUSALEM ARTICHOKE/— A Potential Solar Crop for Food and Energy Supplies

by

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CHAPTER 1

INTRODUCTION

Interest in commercial production of fructose has increased considerably in recent years. Fructose is gradually claiming a larger portion of the sweetening market and is becoming accepted in the beverage, confectionary, baking and canning trades.

The impetus of the energy crisis of 1973 spurred extensive research for finding new low-cost, plentiful raw materials for substitute fuel. Among the raw materials proposed are biomass including cultivated crops. For instance, ethyl alcohol is produced from plant carbohydrate by conversion through fermentation (see, e.g., Miller, 1974; Calvin, 1976), and methane is generated from plant residue through anaerobic digestion (see, e.g., Fry et al., 1973; Clausen et al., 1976; Meynell, 1976).

The available literature shows that the Jerusalem artichoke (Hilianthus tuberosus), a native North American plant which provides solar energy fixation in the form of inulin (a polyfructosan), is a good source of food and energy (Buswell et al., 1939; Underkofler et al., 1937; Pilnik et al., 1976). While some publications are available on fructose production from this crop, little information regarding the alcohol production from this crop has been found, and even less is available on methane production.

Some of the reasons for the increased use of fructose recently may be summarized as follows: (a) The sugar shortage and spiraling prices resulted in greater attention being focused on sugar substitutes (Rounds, 1976); (b) After FDA announced on March 9, 1977 that it would propose a ban on saccharin - the last non-nutritive sweetener in the

U.S., a search by industry for a nutritive substitute with high sweetening power has been intensified (Aminoff, 1974; Anonymous, 1977); (c) The production of fructose is currently in high demand as indicated by the dramatic increase in the production of high-fructose corn syrup (Crocco, 1976; Russo, 1976).

The acceptibility of Jerusalem artichoke as a human food or as an animal feed was evaluated by several investigators. Most of the investigators reported the the Jerusalem artichoke was acceptable as human food but was more acceptable as animal feed (Alleman, 1971; Masson, 1973). The cost of Jerusalem artichoke as a raw material of fructose commercial production can be buffered by a huge utilization raised specifically for food or feed.

If alcohol and methane can be produced from this crop, this not only can buffer the price of fructose but also can solve some energy shortage problems. When fructose price is low, substantial quanitities of fructose syrup can be diverted to the production of alcohol, and when the price of fructose is satisfactory, only the Jerusalem artichoke molasses, by-product of fructose manufacture, need be converted to alcohol. The residues after the alcohol and methane fermentation can also be utilized as animal feed.

By-products are a very important phase of modern industry and the fructose industry from Jerusalem artichoke will be no exception to this rule. The dense top growth, which is often 6-10 ft. high, is removed and utilized as silage or is mixed with molasses and used as a valuable stock food. The Jerusalem artichoke pulp after fructose production can also be utilized as a raw material for anaerobic digestion to produce methane gas. The solid residue after anaerobic digestion can also be

utilized as fertilizer or as feed for animals (Fry et al., 1973). A hypothetical system of Jerusalem artichoke to food and energy is shown in Fig. 1.

The primary objectives of this research were threefold. The first major objective was to investigate the conversion of Jerusalem artichoke to fructose by extraction and hydrolysis. The second major objective was to evaluate the technical feasibility of alcohol production by fermentation and methane production by anaerobic digestion of Jerusalem artichoke. The third major objective was to study the acceptability of Jerusalem artichoke as a food.

Chapter 2 reviews the published literature on several aspects of Jerusalem artichoke, including fructose production, alcohol production and methane gas production from Jerusalem artichoke tubers, and the food value of these tubers. The cultivation of Jerusalem artichoke is described in Chapter 3. In Chapter 4 the experimental results are given for the effects of the sample preparation method, extraction time and temperature on the yield of fructose by simultaneous extraction and conversion of inulin from Jerusalem artichoke tubers. The reaction kinetics of hydrolysis of extracted inulin from Jerusalem artichoke tubers to fructose is described in Chapter 5. Chapter 6 reports the technical feasibility of the alcohol fermentation from Jerusalem artichoke tubers. The technical feasibility of the methane anaerobic digestion from Jerusalem artichoke tubers is described in Chapter 7. The acceptibility of Jerusalem artichoke tubers as food is reported in Chapter 8.

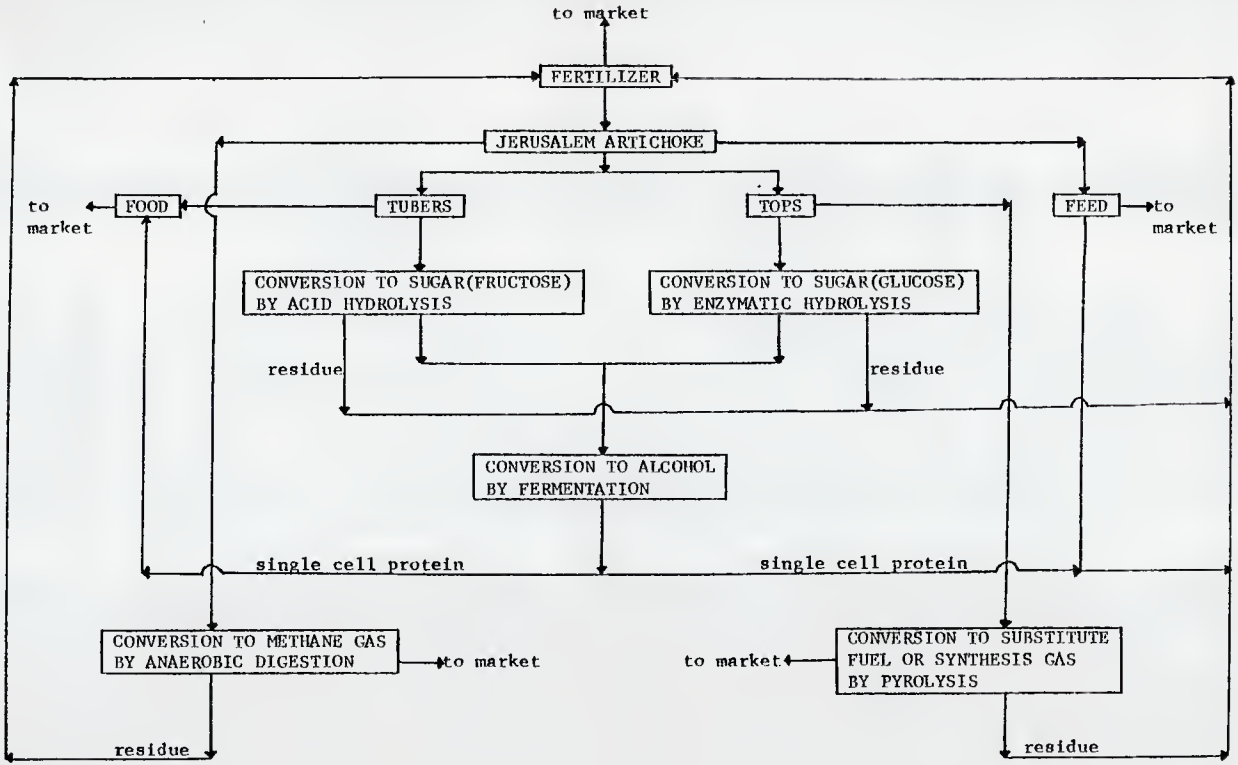


Fig. 1. Hypothetical Jerusalem Artichoke Conversion System for Food, Fuel, Feed and Fertilizer Production — F^4 System (Fan, L. T., 1975).

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CHAPTER 2
LITERATURE REVIEW

INTRODUCTION

Although the Jerusalem artichoke (Helianthus tuberosus L.) is native to North America, its cultivation has been developed on a rather large scale in some parts of Europe but the crop in the United States has remained unimportant (Shoemaker, 1927).

A widespread interest in the plant has developed in this country only during the early 1930's and largely as a result of its possible use as a source of raw material for the manufacture of fructose and alcohol (McGlumphy et al., 1933; Christensen et al., 1937; Underkofler et al., 1937).

This chapter collects, classifies, and reviews the literature on the Jerusalem artichoke. Besides the publications on fructose production from the Jerusalem Artichoke tubers, this review covers publications on other utilization of this plant such as food and feed, alcohol production and methane gas production. In addition, the literature on the characteristics of fructose and its produetion from other sources is reviewed.

JERUSALEM ARTICHOKE, INULIN AND FRUCTOSE

Although the Jerusalem artichoke is a native North American plant having many desirable characteristics, this plant has apparently received little attention in the United Sates and meager effort has been made to improve it. The Jerusalem Artichoke is frequently described as a noxious weed.

In this section, publications related to the Jerusalem artichoke is reviewed. The emphasis will be on the carbohydrates of Jerusalem

artichoke tubers.

1. The Jerusalem Artichoke

1.1 Historical

The Jerusalem artichoke is not an artichoke but a sunflower (Bergh, 1972). It does not come from Jerusalem, and as shown in Fig. 1, its edible portion is more like a potato than the Globe artichoke. The term "Jerusalem" crept into the language as a corruption of the Italian girasole (turn-to-the-sun) for "sunflower" (Reay, 1968). According to Shoemaker (1927), the first published record of the Jerusalem artichoke was given by Champlain who spoke of seeing it in the gardens of the Indians at Nauset Harbor, Cape Cod, Massachusetts, on July 21, 1605, and tasting like artichokes. This also contributed to the confusion. The botanical name of Jerusalem artichoke is Hilianthus tuberosus. It is related to artichokes and sunflowers and is frequently listed in wild flower field guides (Weick, 1943).

As already mentioned, the Jerusalem artichoke was known and grown by the American Indians long before the settlers arrived in the New World and was carried back to Europe by early explorers, cultivated for nearly three centuries, and finally reintroduced into this country in a number of improved varieties (Reay, 1969). The Jerusalem artichoke which had been brought to France found its way first to Holland and then to Rome no later than 1612. As early as 1629, Parkinson in England wrote "Artichokes of Jerusalem may most fitly be called Potatoes of Canada, because their roots are in form, colour and taste like unto the potatoes of Virginia but greater and the French brought them first from Canada into these parts." (Mayfield, 1974). In 1922, Sibley submitted adequate lots of tubers for long range experiment and analysis by the

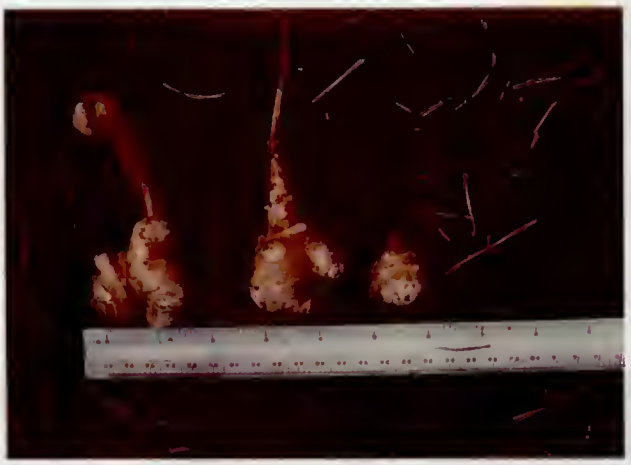


Fig. 1. These Knobby Tubers of Jerusalem Artichoke Have Just Been Harvested.



Fig. 2. The Tall Tops of Jerusalem Artichoke Just After Blossoms.

U.S. Bureau of Standards. Among the improved varieties, the "Mammoth French White Jerusalem Artichoke" which was developed by French horticulturists by careful constant propagation and cross breeding was well known (Jackson, et al. 1926).

During early 1940, the U.S. Department of Agriculture, collaborating with the Oregon State College at Corvallis, took the wildlings of Jerusalem artichoke for improvement. Not only had the tubers lost their uncouth, irregular appearance, but they produced crops which were far in excess of the yield of potatoes (Weick, 1943). There are now more than 200 varieties, the best among them being American artichoke, formerly improved Mammoth French White (Reay, 1969).

It is impossible to predict the outcome of studies in plant breeding but considering the fact that the sugar contents of beet or sugar cane have improved substantially through breeding, it would seem reasonable to expect new varieties of tubers that possess the desirable qualifications of high quality, high yield, and high sugar contents .

1.2 Agricultural aspects

The Jerusalem artichoke is a perennial plant that can grow on almost any type of soil, naturally the richer the better. For instance, it grows well in very sandy soil, but do better in rich sandy loam. Heavy clays are to be avoided because when the roots are pulled, the soil should not adhere to the tubers (see, e.g., Shoemaker, 1927; Natural Resources Intelligence Service, Canada, 1929; Boswell et al., 1936).

The plants reproduce only by means of the tubers, and the tubers of Jerusalem artichoke are planted in the fall or probably are better planted from mid-April through May. This is accomplished by either

small ones used whole or larger tubers in cut up sections not over two ounces. The tubers should have at least two eyes but not over three (Boswell et al., 1936; Weick, 1943). The tubers are planted in rows so that the silage can be cut with a corn binder and the tubers can be dug with a potato digger. They should be planted at least three to four inches deep and three to four feet apart with fifteen to eighteen in a row as the plants tend to become bushy, shaggy, and six to more than ten feet tall depend on the different varieties and soil sites, as shown in Fig. 2. The yellow daisy-like flower of Jerusalem artichoke is shown in Fig. 3., and Fig. 4 shows the stalks of Jerusalem aerichoke which are woody and tough.

The Jerusalem artichoke is very hardy. Frost does not hurt it; rather, it seems to improve its flavor, texture and fructose content (see, e.g., Bacon, et al., 1952; Reay, 1969; Criner, 1970). Also, it withstands drought and is almost completely resistant to insects and plant diseases. It is a very good competitor with weed (see, e.g., Reay, 1969; Allemanend, 1971; Masson, 1973). The Jerusalem artichoke produces satisfactorily on less fertile land. It requires much less fertilizer than potatoes or even requires no fertilizer (see, e.g., Shoemaker, 1927; Sebert, 1974; Anonymous, 1975). The yield of tubers on soils unsuitable for beets is as good or better than that of beets on good beet soils (Mariller, 1943). Encyclopedia Americana states that "Perhaps no other plant is of easier cultivation than the Jerusalem artichoke".

The Jerusalem artichoke was studied with reference to its yield and sugar contents by Boswell et al. (1936) in considerable detail. They investigated 20 varieties of the Jerusalem artichoke that grew in



Fig. 3. The Yellow Daisy-like Flower of Jerusalem Artichoke, Which Is About 3 Inches Across, Is "Rather Beautiful".



Fig. 4. The Stalks of Jerusalem Artichoke Are Tough And Woody.

three different parts of the United States for three different years, and they found that the mean yield per acre was 6.58 tons at Urbana, Ill., 16.73 tons at Crovallis, Ore., and 8.74 tons at Washinton, D.C. The mean yield of the 20 varieties at all three places for three years was 10.69 tons per acre. Haber, et al. (1941) attempted to obtain a high yield of Jerusalem artichoke tubers by using nine varieties; the mean yield of the tubers per acre was 12 tons in 1939 and 15 tons in 1940. Field trials on sandy soils in the Netherlands yielded 20 tons per acre (Pilnik, 1976). Yields of tubers up to 26 tons per acre was obtained in France (Mariller, 1943).

After harvesting, one of the major problems is storage (McGlumphy et al., 1933). Preventing spoilage and conserving moisture content are two important points for Jerusalem artichoke storage, since the very thin skin permits the tubers to lose moisture and become spoiled rapidly when they are exposed to the air at a room temperature.

There is a common and easy way to store the tubers (Traub et al., 1929). Keep the tubers where they are planted and cover with a few inches of loose earth. However, there is a consistent decrease in the fructose-glucose ratio and in the fructose-total sugar ratio (Dorrell et al., 1977). The storage of Jerusalem artichoke at a temperature near the freezing point is also a successful method of keeping a large percentage of the tubers free from rot and shriveling for any length of time after they are dug. Traub, et al. (1929) found that if the Jerusalem artichoke tubers were stored under the conditions of the experiment which was at a temperature range of 32 -35°F and a relative humidity of 89-92 percent, they retained a larger amount of water-soluble carbohydrate per unit green weight than the tubers left

in the ground over winter.

It appears that the expense of refrigeration is a handicap to its commercial development. Also, if the tubers are allowed to freeze solidly, they must be thawed out very gradually; otherwise, they become black and mushy. Such tubers are undesirable since they are difficult to wash, lose part of their sugar contents to the wash water, tend to crush as they are handled, and lose many small pieces of the crushed Jerusalem artichoke tubers containing much juice in the slicer (McGlumphy, et al., 1933).

McGlumphy (1931) investigated the effect of drying by the desiccating method on the carbohydrates present in the ground tubers. He found that the Jerusalem artichoke can be dried without exceeding 80°C for the final temperature, as shown in Table 1, and the fructose-total sugar ratio remains unchanged in dried tubers; the drying also breaks down the cell structure and renders diffusion more easily accomplished; and the storage space required for dried tubers is decreased from one-half to two-thirds that required for the fresh tubers. This desiccating method was utilized by Iowa State University to produce fructose from Jerusalem artichoke tubers by a semi-commercial process (McGlumphy et al.,1933). Coating with chemicals for the storage of Jerusalem artichoke tubers has also been proposed (Dykins, et al., 1933).

1.3 The composition of Jerusalem artichoke

In connection with the utilization of Jerusalem artichoke in fructose manufacture and in other applications, the composition of the tubers is of interest. A knowledge of the composition of the tops is also important because of their value as a food for stock and

Table 1. Effect of Oven Drying on Sugars of Fresh and Dried Jerusalem Artichokes (McGlumphy, 1931)

Sample No.	Treatment	Fructose (%)*	Glucose (%)	Total sugar (%)	Fructose / Total Sugar
1.	Fresh tubers	11.95	2.85	14.80	0.807
2.	Dried at 100°C. 1 hr.	12.04	1.99	14.03	0.858
3.	Dried at 90°C. 1 3/4 hr.	12.12	2.43	14.55	0.833
4.	Dried at 80°C. 2 1/4 hr.	11.90	2.91	14.81	0.803
5.	Dried at 70°C. 2 1/2 hr.	12.21	2.81	15.02	0.812
6.	Dried at 125°C. 1/4 hr. then at 75°C. 1 hr.	11.88	2.98	14.86	0.799

* The percentage given are bases on 30 gm wet sample taken in every case.

as a source of energy. However, little information regarding the composition of the Jerusalem artichoke tubers is available, and even less is available on the composition of the tops.

Traub, et al. (1929) reported the analyses of the composition of Jerusalem artichoke under Minnesota conditions for four varieties— Porland, Mammoth French white, a purple variety, and a variety sent out by the United States Department of Agriculture (U.S.D.A.). The plants were grown on rich sandy loam. A comparison of the composition of the four varieties of tubers is reproduced in Table 2. In the ratio of fructose to total sugars which is an important consideration in the manufacture of fructose, Mammoth French white ranks highest, followed by U.S.D.A., Porland, and the purple variety. The carbohydrates of Jerusalem artichoke tubers will be discussed in detail in the next section. The data covering the composition of tubers, leaves, stems and entire tops of the Porland variety are reproduced in Table 3 which shows the tubers contain much more sugar than the leaves, stems, and entire tops. The contents of total sugar, starch, and protein of the entire tops of Jerusalem artichoke for animal feed, fermentation, and pyrolysis and other purposes are worth examining.

2. Carbohydrates of the Jerusalem Artichoke Tubers

2.1 The carbohydrate content of Jerusalem artichoke tubers

According to Jackson et al. (1926) and Willaman (1922), Tanret classified the carbohydrates of Jerusalem artichoke with a very definite differentiation, as shown in Table 4. This table also contains the data obtained from the paper, No. 519, of the Bureau of Standards (1926) and Willaman's (1922) "The Preparation of Inulin, with Special Reference to Artichoke Tubers as a Source". In addition, Table 4 contains a

Table 2. Composition of the Tubers of Four Jerusalem Artichoke Grown on Sandy Loam at University Farm, St. Paul, Minn. (Traub et al., 1929)

Variety	Composition expressed as percentage of green weight (%)							
	Moisture	Dry Matter	Fructose	Glucose	Total Sugar	Ash	Crude Protein	Crude Lipids
Mammoth French White	79.10	20.80	10.30	4.79	15.09	1.24	1.75	0.24
Porland	79.80	20.10	9.99	5.06	15.05	1.08	2.56	——
Purple	80.20	19.70	9.33	4.43	13.96	1.16	2.62	——
U. S. D. A.	78.90	21.00	9.38	4.74	14.12	1.18	3.06	——

Table 3. Composition of Tubers, Leaves and Stems of Jerusalem Artichoke of the Porland Variety, Grown at University Farm, St. Paul, Minn. (Traub et al., 1929)

Determinations	Percentage of green weight in -			
	Tubers	Leaves	Stems	Entire Tops
Moisture	79.8	75.8	66.1	69.9
Dry matter	20.1	24.1	33.8	30.0
Reducing sugars	——	1.72	1.96	1.86
Non-reducing sugars	——	2.03	6.03	4.44
Total sugars	15.04*	3.75	7.99	6.30
Starch	——	1.02	6.25	4.48
Pentosan	0.83	2.07	0.42	1.07
Protein (%N x 6.25)	2.56	3.75	0.93	2.00
Ash	1.08	3.58	0.74	1.87
Crude Lipids	——	0.17	0.04	——

*Total water-soluble carbohydrates.

Table 4. Tanret's Classification of Polysaccharides Existing in the Juice of the Jerusalem Artichoke (Tanret, 1893)

Carbohydrates	One liter of juice contains	per cent of total sugars	Molecular weight	$[\alpha]_D$	Parts water required to dissolve 1 part at 15°C	Action of brewers' yeast
	g					
Inulin	51.0	20.0	4827	-39.5	10000	Unfermentable
Pseudo-inulin	0.6	0.3	2610	-32.2	350-400	Do.
Inulenin	24.0	9.0	1645	-29.6	8	Do.
Helianthenin	14.4	6.0	1924	-23.5	1	Difficulty fermentable
Synanthrin	122.0	50.0	1319	-17.0	*	Fermentable
Sucrose	30.0	12.0	342	+68.4**	*	Do.
Reducing sugar	9.0	3.0	180	--	*	Do.

* All portions

** The data of $[\alpha]_D$ of sucrose is from CRC Handbook of Chemistry and Physics 56th edition (1975-1976).

summary of the properties of these compounds. It is apparent that the carbohydrates of lower molecular weights and relatively high solubilities predominate in the juices. However, all compounds are condensation products of fructose. The least soluble polyfructosan is the starch-like polysaccharide known as inulin which has gummy characteristics and occurs abundantly in dahlias. The other compounds, pseudo-inulin, inulenin, helianthenin, and synanthin, are much more soluble than inulin and termed "Levulins" or "Inulides" (Jackson et al., 1926; Bacon et al., 1951).

Jackson et al. (1926) expressed the opinion that the carbohydrates of Jerusalem artichoke did not permit such definite differentiation and that there is a more or less continuous series of substances with a continuous variation in properties. They have structures similar to the polymer homologs of the order of inulin. The differences among them depend on the differences in their branching structures of fructose polymers and on the chain lengths of the polymers (Schlubach, 1952). Most of the recent papers consider that disaccharides (sucrose or difructose anhydride), inulides, and inulin are the only major carbohydrate constituents in the tubers (Torchinskeya, 1968; Taniguchi, et al., 1972, Plinik et al., 1976). From the standpoint of fructose manufacture it is not important to identify these compounds. As long as these compounds are hydrolyzed, they produce fructose as a major end product.

The carbohydrate or sugar contents of the Jerusalem artichoke tubers are influenced profoundly by variety and locality, as mentioned earlier. A six-year mean analysis of the 20 varieties of Jerusalem artichoke investigated by Boswell et al. (1936) showed 13.33% fructose and 16.38%

total sugars on a wet basis. Haber et al. (1941) investigated the fructose contents of nine varieties of Jerusalem artichoke in successive years under Iowa conditions, and found that the fructose contents ranged from 3.70% to 6.55% in 1939 and from 8.40% to 17.64% in 1940. Chubey et al. (1974) made a survey on reducing sugar and fructose contents of Jerusalem artichoke tubers under prairie conditions at the Research Station, Morden, Manitoba in Canada, and found that a high tuber yielding Russian strain, on a wet basis, had a mean reducing sugar contents of 17.0%, of which 76.8% was fructose and 13.5% was glucose. One native Manitoba strain contained up to 27.7% reducing sugar with 75.3% fructose and 14.9% glucose, Pilnik et al. (1976) has published a review of the literature on Jerusalem artichoke as a source of fructose; his review indicated that Jerusalem artichoke is a good source of total sugar (15-18%) with a high proportion of fructose (75-87%).

There are some factors that affect the carbohydrate contents of Jerusalem artichoke tubers. Bacon et al. (1951) investigated the carbohydrate changes in tubers of the Jerusalem artichoke during the period June, 1950 to May, 1951, and found that a change in the positive direction of the optical rotation of the artichoke extract could be correlated with an increase in the proportion of carbohydrate components of lower molecular weights estimated by a quantitative paper-partition chromatography. Traub et al. (1929) demonstrated that there was a steady loss of fructose-yielding polymers with a corresponding increase in the glucose-yielding polymers. They found that the ratio of fructose to total sugar decreased, but the ratio of fructose to glucose decreased at a much faster rate. Chubey et al. (1974) also found that the contents of reducing sugar and the fructose-glucose ratio generally

declined with later harvest. Depolymerization of fructose residues occurring during the growth of daughter plants of Jerusalem artichoke also was observed by Jefford et al. (1960).

Factors related to the carbohydrate change of Jerusalem artichoke tubers cannot be neglected for fructose production. The time for harvest, the storage conditions, and others should be controlled in order to yield plants high in sugar contents and high in the ratio of fructose-total sugar.

2.2 Properties of inulin from the Jerusalem artichoke tubers

Inulin is widely distributed as a storage carbohydrate in the root organs of the Compositae (sunflower family) and allied families of plants. The tuberous roots of the dahlia, dandelion, chicory, Jerusalem artichoke, arnica and pyrethrum are other examples of plant materials rich in inulin (Browne,1912). In the Jerusalem artichoke tubers a mixture of carbohydrates is present. Among them sucrose is the component with the smallest molecular weight and inulin probably the largest (Edelman et al., 1951).

According to Harding (1923), inulin was discovered from the tubers of the Jerusalem artichoke by Rose in 1805 but it was first prepared from the dahlia tubers by Payen in 1823. It has long been evident that inulin may constitute only a small fraction of the total carbohydrate present in the Jerusalem artichoke tubers; the remainder resembling inulin is composed essentially of fructofruanose units, but having a greater solubility in water and in aqueous ethanol than inulin (Bacon, 1951).

The structure of inulin consists of linear chains of D-fructofuranose molecules which are united by β(2→1) linkages and are terminated by a

non-reducing α-D-glucopyronose residue attached as in sucrose. The arrangement of the sugar residues in inulin is as follows (Barnett et al., 1976):

$$\beta\text{-D-Fruf } 2(\rightarrow 1\ \beta\text{-D-Fruf } 2)_n \rightarrow 1\ \alpha\text{-D-Glup}$$

where (Fruf) is a fructofuranosyl group or residue, (Glup) is a glucopyranose residue, and n may be any number from zero (sucrose) to about 35 (inulin). It is this terminal glucose unit that causes inulin hydrolysates to contain a relatively small amount of glucose (< 20%) (Jefford, 1960). The structure of inulin is shown as Fig. 5 (Eldeman et al., 1971; Pilnik et al., 1976).

Inulin (plant starch) has a composition of the formula $(C_6H_{10}O_5)_n$ with varying amounts of water of hydration and is levorotatory. Harworth et al. (1932) found that inulin was composed of about 30 D-fructose residues and had a molecular weight about 5000. Some of the chemical and physical properites of inulin are listed in Table 5 (Browne, 1912; Harding, 1923; Hibbert et al., 1931; Wain et al., 1964).

Inulin consists of a white hygroscopic substance and is very slightly soluble in cold water but very soluble in hot water (Jackson, 1926). The expressions, "insoluble" and "slightly soluble", are commonly applied to inulin in the literature, but actual measurements recorded are very few for inulin from the Jerusalem artichoke tubers. Since the solubility of dahlia inulin differs considerably from that of chicory inluin, it appears that the source of inulin affects its solubility (Stephen, 1963)..

A Russian article (Rominski, 1955) shows that when inulin from Jerusalem artichoke was hydrolyzed rapidly in 0.14 N HCl

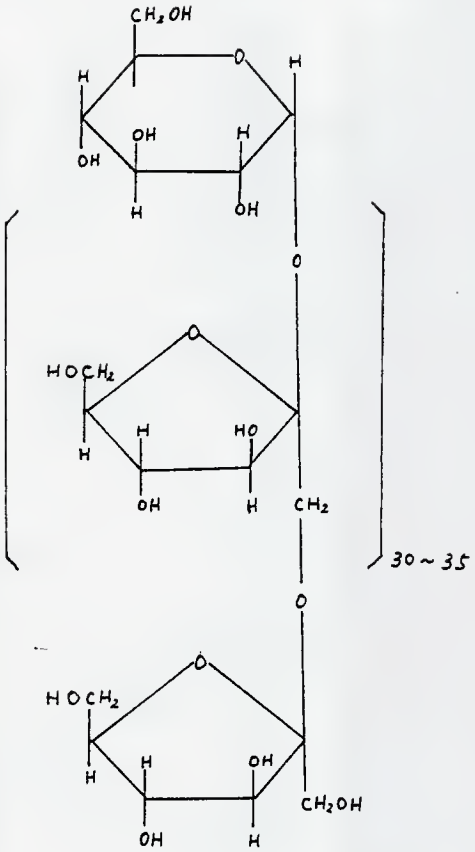


Fig. 5. Structure of Inulin(Eldeman et al., 1971; Pilnik et al., 1976).

Table 5. Chemical and Physical Properties of Inulin (Browne, 1912; Harding, 1923; Hibbert et al., 1931; Hein et al., 1964)

Emperical formula:	$(C_6H_{10}O_5)_n$
Structure:	as shown in Fig. 5
Molecular weight:	5000
Melting point:	178°C
Specific rotation:	$[\alpha]_D^{20} = -38.3$
Appearance:	sphere crystals
Color:	white
Hygroscopicity:	fairly hygroscopic
Solubility in cold water:	sparingly soluble
Hot aqueous solution on cooling:	limpid
Prolonged heating with water at 100°C:	hydrolyzed to fructose
Hydrolysis with acid:	fructose
Lime water:	no precipitate
Lead subacetate:	no precipitate
Ammonioeol lead acetate:	Precipitate
Boiling Fehling's solution:	slowly reduced
Iodine:	no action

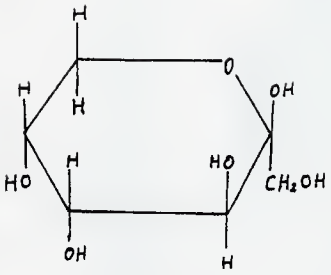
at 85°C, glucose, fructose and anydides of difructose were formed, and when inulin was hydrolyzed with amounts of cationite and H_2O equivalent to 0.1 N HCl for 4 hrs. at 90°C, only glucose, sucrose, fructosan, mixed fructosan, and another fructosan were formed. (It seems most probable that the latter three are anhydride difructose, inulides and inulin). However, inulin was hydrolyzed completely in 0.14 N HCl at 85°C for 35 minutes.

2.3 Fructose — the possible sucrose substitute and its properties

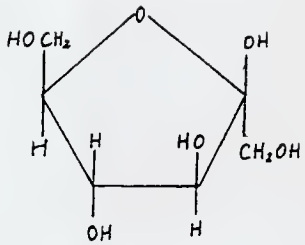
Fructose was isolated and identified more than 125 years ago by the French chemist, H. P. Dubrunfaut (Browne, 1912). It is a monosaccharide, a reducing sugar, and widespread in nature. Generally speaking, it is one of the most chemically reactive of the natural sugars (Arnold, 1971).

In spite of its widespread natural occurrence, however, fructose in pure and particularly crystalline form has traditionally been relatively scarce and expensive. It is considered mostly as a laboratory material or as a pharmaceutical speciality in nutritional therapy. This scarcity has been due to the complicated and laborious methods of isolating and crystallizing fructose in pure form (Doty, 1976).

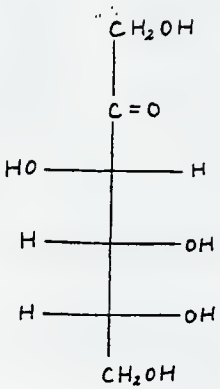
The structure of fructose in different configuration is shown in Fig. 6 (Doty et al., 1975). Some of the chemical and physical properites of fructose are listed in Table 6 (Hibbert et al., 1931; McGlumphy et al., 1931., Verstraeten, 1967; Doty et al., 1975). One of the important characteristics is that fructose readily forms an inorganic additive compound - calcium fructosate, $C_6H_{12}O_6 \cdot CaO \cdot 6H_2O$. This compound has a solubility of only 8.5 g/l of water at 15°C, and



β-D-FRUCTOPYRANOSE



β-D-FRUCTOFURANOSE



KETO-D-FRUCTOSE

Fig. 6. Structure of Fructose in Different Configurations; the Furanose is the Sweetest (Doty et al., 1975).

Table 6. Chemical and Physical Properties of Fructose (McGlumphy et al., 1931; Verstraeten 1967; Doty et al., 1975)

Empirical formula:	$C_6H_{12}O_6$
Structure:	as shown in Fig. 6
Molecular weight:	180
Melting point:	103-105°C.
Specific rotation:	$[L]_D^{20} = -133° \longrightarrow -92°$
Hygroscopicity:	more hydroscopic than sucrose, dextrose
Relative sweetness:	as shown in table 7
Viscosity:	lower than sucrose
Solubility in water (20°C):	as shown in Fig. 8
Solubility in 100% alcohol:	sparingly soluble
Solubility in 100% methanol:	sparingly soluble
Appearance:	needle crystal
Color:	white
Boiling Fehlings solution:	reduced
Iodine:	no action

is used in the purification of fructose.

Other characteristics of fructose and its potential and actual uses are given below:

Sweetness. Fructose is generally recognized as the sweetest of the naturally occuring sugars (Shellenberger, 1971). The relative sweetness of various sweeteners including sugar, corn syrups, polyols, and non-carbohydrate sweet chemicals is shown in Table 7 (Amerine et al., 1965; Inglett, 1971; Redfern et al., 1972; Beck, 1974; Lee et al., 1976). The relative sweetness of fructose reported in the literature, however, ranges from around 1.00 to more than 1.80 while the sweetness of sucrose in similar conditions is taken as 1.00 (Shellenberger, 1971). All of the reported values are probably valid. The sweetness of fructose has been observed to be affected by various factors such as that carrier medium in which it is tested, and particularly by temperature and pH.

Fructose is a mixture of anomeric forms in a solution comprising both pyranose and furnaose rings in the α or β configuration (Barker, 1976). The configuration of the fructose structure also affects its sweetness. Three configurations of fructose are shown in Fig. 6, of which the furanose is the sweetest. Furanose is also the major constituent of inulin in Jerusalem artichoke tubers (Doty et al., 1975; Pilnik et al, 1976).

The caloric contents per gram of fructose are the same as for other carbohydrates, but since less could be used for a given sweetness there could be a moderate reduction in caloric value (Lee et al., 1976).

The polysaccharide material, inulin, which serves as a starting point for the preparation of fructose is a potential sweetener in

Table 7. Relative Sweetness of Various Sweeteners (Amerine, 1953; Inglett, 1971; Redfern et al., 1972; Beck, 1974; Lee et al., 1976)

Nutritive*	Relative** Sweetness	Non-nutritive***	Relative Sweetness
Fructose (Levulose)	1.00-1.80	Monellin	2500
Sucrose	1.00	Thoumatin	1600
42%Fructose corn syrup (Isomerose)	1.00	Dihydrochalcone	300
Honey	0.97	Saccharin	300
Maltitol	0.95	Stevioside	300
30%Fructose corn syrup	0.93	Dulcin	200
Xylitol	0.90	Aspartame	100
Glucose (Dextrose)	0.74	Cyclamate	30
Molasses	0.74		
Extra high corn syrup	0.73		
Mannitol	0.72		
Sorghum	0.69		
Regular corn syrup (DE 38-47)	0.50		
Sorbitol	0.40		
Lactose	0.40		
Maltose	0.32		
Corn syrup (DE 28)	0.30		

* Sugars and polyols ** Sucrose as standard=1 *** Non-carbohydrate sweet chemicals.

Jerusalem artichoke tubers (Barker, 1976).

Solubility and Hygroscopicity. Fructose is the most soluble of all the sugars in water, the concentration of a saturated solution at 20°C being 78.94% as shown in Table 8 (Jackson et al., 1926; Doty et al., 1975). The high solubility of fructose tends to prevent the crystallization of other sugars in the presence of fructose. For instance, sandiness in ice cream can be prevented by including a proper amount of fructose in it because it prevents the crystallization of lactose in milk (McGlumphy, 1933).

The hygroscopic property of fructose makes it an excellent humectant. It has a greater ability to absorb and retain moisture than sucrose or glucose (Henry, 1976). For example, cream fillings and frostings in various confections, which are formulated with fructose, usually stay moist and fresh longer and have a significantly extended shelf life.

Medical Uses. Fructose has long been used as a constituent of infant foods, of cough medicines, and of other therapeutic preparations. It has also been found effective in the prevention of hyperacidity of the gastric juice (McGlumphy, 1933). However, the most important potential perhaps is the possibility of its application in the treatment or prevention of diabetes. A key factor for diabetics is that almost 80% of all diabetics are obese and a reduction in obesity is one of the most important requirements of dietary treatment. Fructose, because of its greater sweetness than sucrose, permits a caloric reduction in the diet (Marks, 1971). Fructose is also less cariogenic than sucrose and glucose (Makinen, 1972).

Flavor, Color, Aroma. The inimitable delicate flavor of many fresh fruits is partially dependent upon the fructose, and the characteristic flavor of honey is due in part to the high percentage of fructose. The characteristic fruit flavor of fructose makes it desirable for improving

Table 8. The Solubility of Fructose, Glucose and Sucrose in Saturated Aqueous Solution at Various Temperatures (Jackson et al., 1926; Doty et al., 1975).

Temperature (°C)	Fructose		glucose		Sucrose	
	%(wt.)	g/100g H_2O	%(wt.)	g/100g H_2O	%(wt.)	g/100g H_2O
20	78.94	375	66.60	88	47.11	199
25	80.29	407	—	—	—	—
30	81.61	445	68.18	120	54.64	214
35	82.98	488	—	—	—	—
40	84.34	539	70.01	162	61.84	233
45	85.64	596	—	—	—	—
50	86.90	663	72.04	264	70.91	258
55	88.10	740	—	—	—	—

not only the flavor of many canned foods, but various aromatic seasonings as well. This is especially true in the canning of fruits since it seems to bring out markedly the pleasant fruit flavor (Doty, 1976).

According to Emodi (1978), fructose and glucose are the only two current substitutes for sucrose in use that undergo Maillard-type reactions and caramelization to form aromatically pleasant combinations with amino group of various proteins. Use of small amount of fructose in baked goods contributes to rich golden-brown crusts. On the other hand, this same activity can sometimes lead to off-flavors or discoloration at a low pH and at a high fructose concentration, and upon heating or storing, cause unfavorable reactions with certain pigment substances (Doty, 1976).

Others. The use of dextrose syrup (corn sugar) could be greatly increased by mixing it with crystalline fructose, thus raising its sweetening power and fermentability in baked products (Saussele, 1976). The low viscosity and reduced tendency to crystallization of the resulting syrup makes its handling, storage and blending easy and convenient.

The synergistic effect between fructose and saccharine is also marked. Fructose has been shown to effectively mask the characteristic metallic or bitter after taste of saccharin and this mixture has only 30 to 40% of calories compared to equally sweet (Barker, 1976). The Food and Drug Administration proposed to ban saccharin on March 9, 1977; however, the synergistic property of fructose with other sweeteners is still a great benefit.

FRUCTOSE PRODUCTION FROM JERUSALEM ARTICHOKE TUBERS

According to Aminoff (1974), fructose, the sweetest of all known sugars, has a long production history. The first production method used inulin-containing plants like Jerusalem artichokes, dahlias, or chicory in which fructose was isolated from the inulin hydrolyzate by precipitation of the calcium-fructosate. This was superseded by separating fructose from inverted sugar solutions of sucrose (Verstraeten, 1967). One method which enjoys widespread use currently is the microbilogical or enzymatic isomerization of glucose to fructose from starch (Schaffer, 1972).

Since the raw material for these production processes is inulin-containing plants, cane and beets, corn and other starch-containing plants, it is of interest to investigate the development of the various processes used in fructose production.

1. History of Fructose Production from Jerusalem Artichoke Tubers

1.1 Occurrence of fructose

Fructose, levulose, or as it is colloquially known, fruit sugar, is not rare; next to glucose and xylose it is one of the most abundant suagrs in nature (Doty, 1976). It is rarely found pure in nature; the free state occurs in almost all sweet fruits and berries. It also accounts for half of the sugar content of honey. It is commonly found as a component of saccharides. The combined forms include such combinations as half of the sucrose molecule, and as the basic building block of inulin, the fructose counterpart of starch. Other combinations include raffinose, stachose, gentianose, and similar carbohydrates. These saccharides may be broken down into their component parts by acid or enzyme treatment, thus yielding their share of fructose (Browne, 1912).

Some of the fructose-yielding or inulin-yielding plants include the elecompane, dahlia, chicory, dandelion, canadian thistle, goldenrod, Jerusalem artichoke, wild onion, camas, and burdock (Arsem, 1928). Among these plants, the dahlia, chicory and Jerusalem artichoke seem to be the most promising because their frucose contents are high, and they are easy to grow. Haber (1941) compared the advantages and disadvantages of chicory, dahlia and Jerusalem artichoke under Iowa conditions as an agricultural crop and source of fructose. The dahlia and chicory possess a higher fructose content than the Jerusalem artichoke, but this advantage is overshadowed by the agricultural difficulties encountered in their large-scale production.

1.2 Fructose production from inulin-yielding plants

The relative newness of the commercial availability of fructose, particularly in the United Sates where there has been literally no significant supply before early 1975, has meant that its potential has been largely unnoticed and undeveloped (Doty et al., 1975). There has also been little publicity given to the fact that fructose can be produced from Jerusalem artichoke tubers by methods readily adaptable to industrial operations, at costs within the range of commercial development.

The history of the discovery and methods of preparation of fructose and its parent substance, inulin, was presented by Harding (1923). According to him, inulin was discovered in 1805 by Rose, and the name was first used by Thomson in 1811. McGlumphy et al. (1933) reported that the Frenchman, Braconnot, succeeded in isolating a starchlike substance, inulin, from Jerusalem artichoke tubers in 1824, and Crookewitt hydrolyzed inulin and obtained an "uncrystallizable" sugar

in 1843. The "uncrystallizable" sugar was later crystallized by Jungfleisch et al. in 1880; it had been produced earlier by Dubrunfaut, from sucrose, in 1847. This sugar is known today as fructose.

Willaman (1922) seems to have been the first to propose the Jerusalem artichoke as a source of fructose in commercial quantities, and his suggesion was subsequently pnrsued by Jackson and his coworkers (1926) with the support of the United States Bureau of Standards and by other investigators (see, e.g., Hoche, 1927; Arsem, 1928a). Based on Willeman's proposal on the old Crookewitt method which consists of the isolation and purification of inulin, succeeded by its hydrolysis to produce fructose. He suggested the following scheme as a possible procedure for tbe manufacture of fructose syrup (the origin of pure crystalline fructose): extraction of juice in water by diffusion; clarification by means of lime, phosphoric acid, and carbon; acid hydrolysis of all inulin bodies; precipitation of lime-fructosate; decomposition of lime-fructosate; and evaporation of the fructose solution to syrup.

In 1926, Jackson et al. supported by the U.S. Bureau of Standards, demonstrated that fructose can be prepared at a moderate cost from the Jerusalem artichoke and dahlia. Their method includes the following steps: extraction, hydrolysis and defecation, after which the total reducing sugar of the filtrate is tested. These steps are followed by preliminary precipitation of the sugar as the calcium salt.

The calcium-fructosate is then subjected to carbonation, and the sugar is crystallized directly. Part of the flow sheet of the method is shown in Fig. 7. The step in which fructose was separated from the converted Jerusalem artichoke juices is essentially the same

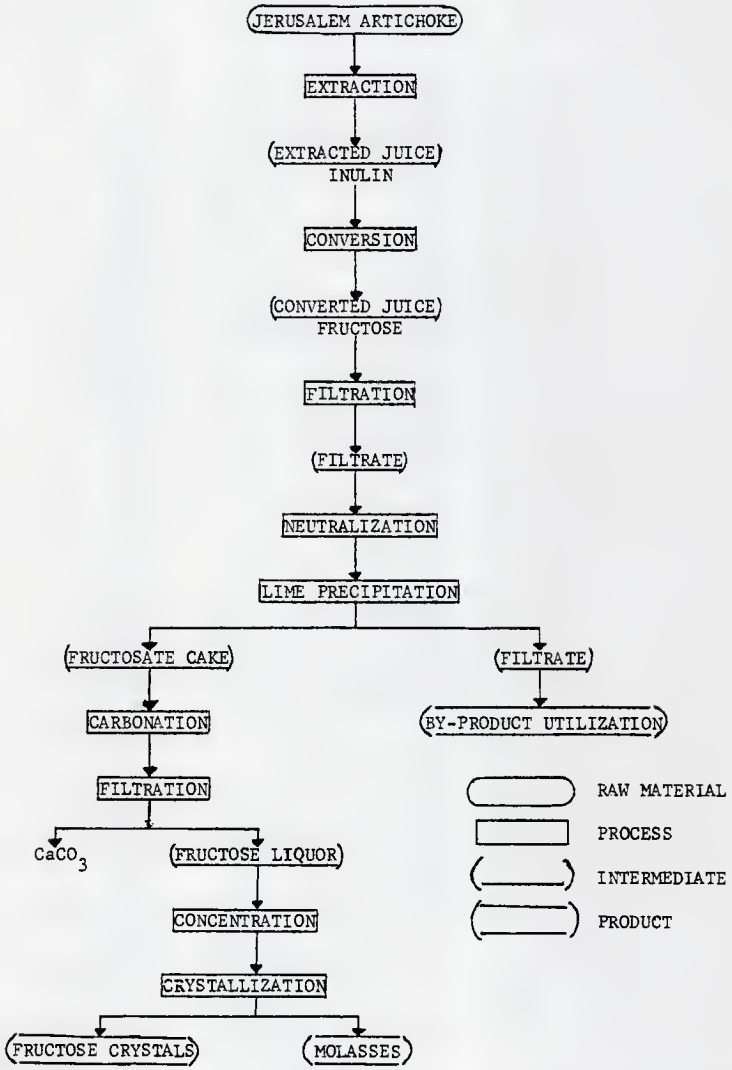


Fig.7. Flow Sheet of Preparation of Fructose from Jerusalem Artichoke (Jackson et al., 1926).

as in the old Dubrunfaut method, but it uses a revised technique to produce larger and more filtrable particles of lime-fructosate. The procedure followed very closely that suggested by Willaman (1922), with the exception that hydrolysis was accomplished before clarification.

Hoche (1927) also tried to use the Crookewitt method on a factory scale. Chicory was the raw material used. Both Hoche (1927) and Jackson et al. (1926) were able to crystallize fructose from an aqueous sclution without the use of organic solvents.

Arsem (1928b) secured two patents, the first covering the clarification of inulin-bearing juice and the second covering the hydrolysis of the polysaccharide contained in the residue after inulin had been removed from the juice. Dahlia was the raw material used.

During the early 1930's widespread interest developed in the growing of fructose-yielding crops, and efforts were made toward the production of crystalline fructose from Jerusalem artichoke tubers. McGlumphy and his coworkers (1933) have summarized the history of fructose up to the year 1933, and have classified all of the attempts to prepare fructose under three general types: Crookewitt method, Dubrunfaut method, and Harding method. The first two methods have been described. In the third method, fructose was separated from glucose with glacial acetic acid with sucrose being the raw material. This method was deemed unsuitable for commercial purposes by the originator's own testimony (Harding, 1923). Meanwhile, McGlumphy and his coworkers (1931, 1932, 1933) succeeded in developing a semi-commercial processing plant capable of producing 50 pounds (22.7 kg) of fructose per day from Jerusalem artichoke tubers at Iowa State University. This

system utilized a continuous precipitation process and yielded very granular lime fructosate. Their method was essentially the same as the U.S. Bureau of Standard's method which was investigated by Jackson and his coworkers.

Almost at the same time, Dykins and his coworkers (1931, 1933) at the University of Illinois, were interested in producing a palatable syrup from Jerusalem artichoke tubers without a process of crystallization. They found that the composition of the syrup depended on the variety of the Jerusalem artichokes utilized, the time of harvest, and the conditions of stroage prior to slicing and drying.

In order to prepare a palatable artichoke syrup, Hardy (1933) tried to purify and acidify an inulin solution by electrodialysis, and Kleiderer (1931) attempted to hydrolyze pure inulin under pressure without introducing a reagent. Syrup obtained from both of these methods has a very satisfactory appearance and taste.

During 1935-1937, Proffitt and his coworkers demonstrated an efficient extraction of Jerusalem artichoke juices by using a diffusion battery (extractors for leaching). They investigated the effect of different shapes and sizes of the cossettes prepared from Jerusalem artichoke tubers on the rate of extraction; the cossettes cut with the usual form of beet knife and handled in large masses would present excessive resistance to the flow of the flood liquid.

After the period of 1930-37, no apparent interest was shown in the manufacture of fructose for Jerusalem artichoke tubers on a commercial-scale in the United States. The majority of the research carried out after this period was concerned with the chemical nature of carbohydrates of Jerusalem artichoke tubers. Bacon and Eldeman (1951) made a survey of the carbohydrates

present in the tubers of Jerusalem artichoke, using paper partition chromatography.

According to Pinlnik et al. (1976), Conti (1953) recommended the production of an ion-exchange-purified hydrolysate directly from Jerusalem artichoke tubers. This mixed syrup would be composed of 70-80% fructose, 15-25% glucose, and 3-7% difructose-anhydrides. Such a product was on the market in the U.S. before World War II. However, low sugar prices impeded any commercial success of fructose production from Jerusalem artichoke tubers.

In Canada, the Natural Resources Intelligence Branch, Department of the Interior, investigated the uses of Jerusalem artichoke from the industrial, agricultural, and economic points of view during late 1930. This plant was highly recommended as a raw material for fructose production. In 1974, Chubey et al. repeated the suggestion of using Jerusalem artichoke as a potential fructose crop for the prairies. He and his associates (1977) made a survey of the effects of irrigation, fertilization, harvest dates, and storage on the reducing sugar and fructose concentrations in Jerusalem artichoke tubers. They found that this crop did not appear to require a high level of management to produce a good quality carbohydrate product. The cultivars appear to have more effect on sugar concentration and quality than do management practices.

During World War II, there was a shortage of food and a limitation of imported sugar in Japan. Yamazaki (1954) reported that the Japan Fructose Company manufactured 127 tons of pure crystalline fructose from 6000 tons of Jerusalem artichoke tubers. The company employed the Dubrunfaut method, used previously by Iowa State University. Yamazaki also reported on other

aspects of fructose production from Jerusalem artichoke tubers, for instance, utilization of waste liquor, labor, and cost.

In the Netherlands, Pilnik et al. (1976) investigated the yields and total sugar of Jerusalem artichoke tubers. According to the results of field trials in sandy soils, up to 8 tons of total sugar per hectare may be obtained. Fructose produced from Jerusalem artichoke tubers was recommended as an attractive alternative to sucrose if economically feasible. From the review given in the article by Pilnik et al. (1976), Jerusalem artichoke is a good source of total sugar with a high proportion of fructose; such fructose products could be made simply and efficiently.

The Jerusalem artichoke has been grown and investigated in Europe, Canada, Russia, Japan, and America several times in this century, and small industrial plants have been proposed intermittently and primarily on a trial basis for the production of fructose. But each time agricultural, technological, and economic problems have discouraged its use in commercial fructose production. However, the commercial-scale production of fructose from Jerusalem artichoke tubers is definitely worth examining again with the present trend toward greater utilization of fructose, the availability of improved cultivars, and the advanced processing methods. Particularly, the advanced processing methods that can be incorporated into the fructose production process, such as chromatographical separation, immobilized enzymatical technology, Talofloc clarification processes may solve the technological and economic problems happened before (Cantor, 1974; Mermelstein, 1975; Bennett, 1977). Membrane ultrafiltration and reverse osmosis membrane filtration may be good methods for the concentration of extracted polysaccharide (inulin) or converted fructose obtained by hydrolysis (Fan, 1976).

1.3 Fructose production from other sources

The properties of fructose, and its production from inulin-containing plants have been discussed. To examine the feasibility of fructose from Jerusalem artichoke tubers as a new industrial sweetener for food, it is desirable to know processes of fructose production from other sources, and characteristics of industrial carbohydrate sweeteners for food.

The fructose content and total carbohydrate content of some common foods are shown in Table 9 (Watt et al., 1963, Harding et al., 1965).

Fig. 8 shows the carbohydrate sweeteners in industrial production (Aminoff, 1974). Notice that in this figure,

a. The materials in frames are currently in industrial production for food purposes.

b. Fructose can be produced from inverted sugar, which is obtained from starch-containing plants and sucrose (cane and beet).

c. Fructose produced from inulin-containing plants was in industrial use earlier, but due to the economic, agricultural, and technological problems, it does not exist at present.

2. Current Sweetener Market and Fructose Production in the United States

2.1 Current sweetener market in the United States

The United States sweetener market is a multi-product, multi-industry complex. Among the products generally included in this market are the following: sucrose sweeteners (cane and beet sugar); starch sweeteners (dextrose, conventional corn syrups, high-fructose corn syrup); other caloric sweeteners (honey, maple syrups and sugar, molasses, sugarcane syrup, refiners' syrup); and non-caloric sweeteners (saccharin and others) (Walter, 1974).

With respect to current developments, there are few of note; however,

Table 9. Average Fructose Content in Common Foods

Food	Fructose content* (g/100g of edible portion)	% Total carbohydrate** (g/100g of edible portion)
Apple	5.0	14.5
Cantaloupe	0.9	7.5
Cherry	7.2	17.4
Grape (white)	8.0	15.7
Grapefruit	1.2	10.6
Honey	40.5	82.3
Peaches	1.6	9.7
Pineapple	1.4	13.7
Pear	5.6	15.3
Potato	0.1	17.1
Raspberry	2.4	15.7
Tomato	1.2	4.7

* Source : Harding et al. (1965)

** Source : Watt and Merrill (1963)

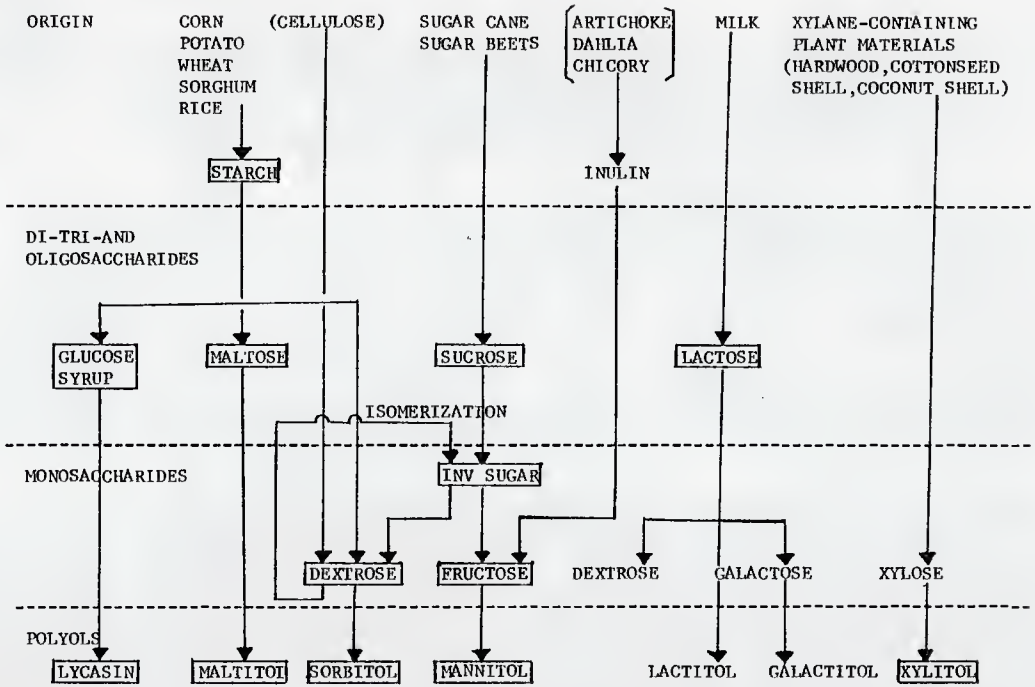


Fig. 8. Industrial Carbohydrate Sweeteners for Food (Aminoff, 1974).

five are worth mentioning. First, the total per-capita sweetener consumption has increased. The data in Fig. 9 shows the pattern of distribution of total sweeteners, of total sugar, and of corn sweeteners (Anonymous, 1976). Excessive consumption of total sweeteners has been implicated in a number of human disorders: dental caries, excessive calories, diabetes, heart disease. This reflects the human craving for sweetness (Pangborn, 1975).

Second, the per-capita consumption of the sucrose sweeteners has increased, but the market share of these sweeteners has decreased (Mitchell, 1974). One of the reasons for this decrease is a growing tendency to look upon sucrose as a not-so-beneficial part of the diet (Aminoff, 1974).

Third, sugar prices spiraled to unprecedented highs in 1974, caused by the lag of production behind consumption. Fig. 10 shows the fluctuating sugar prices between 1956 and 1976 (Troy, 1977). In 1975, about half of the sugar was in the form of processed foods, one-fourth in soft drinks, and the remaining fourth in household sugar (Pangborn, 1975). The industrial users are able and willing to substitute one sweetener for another, whatever economics dictates. This is the other reason for the decreased market share of sucrose sweeteners.

Fourth, the per-capita consumption of both the starch sweeteners and the non-caloric sweeteners has increased, and their relative shares of the market have increased (Walter, 1974, Rosenzweig, 1976). In 1972, cane, beet, and corn shares of the sweetener market were, respectively, 57.7, 24.7, and 16.6%. Recently, advances in enzyme technology have allowed corn processors to produce high-fructose corn syrup, which greatly enhanced the growth rate of starch sweeteners (Russo, 1976). Accordingly, the comparable shares of market by cane, beet and corn could easily reach 38.8,

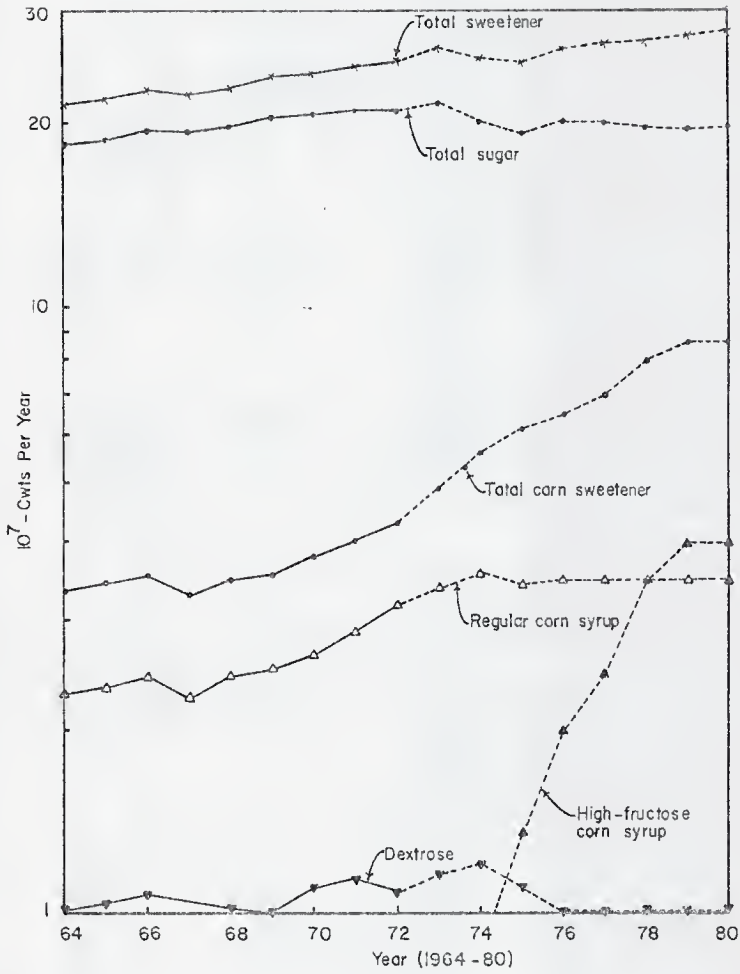


Fig. 9. Trends in Sweetener Use Basis (Anonymous, 1976).

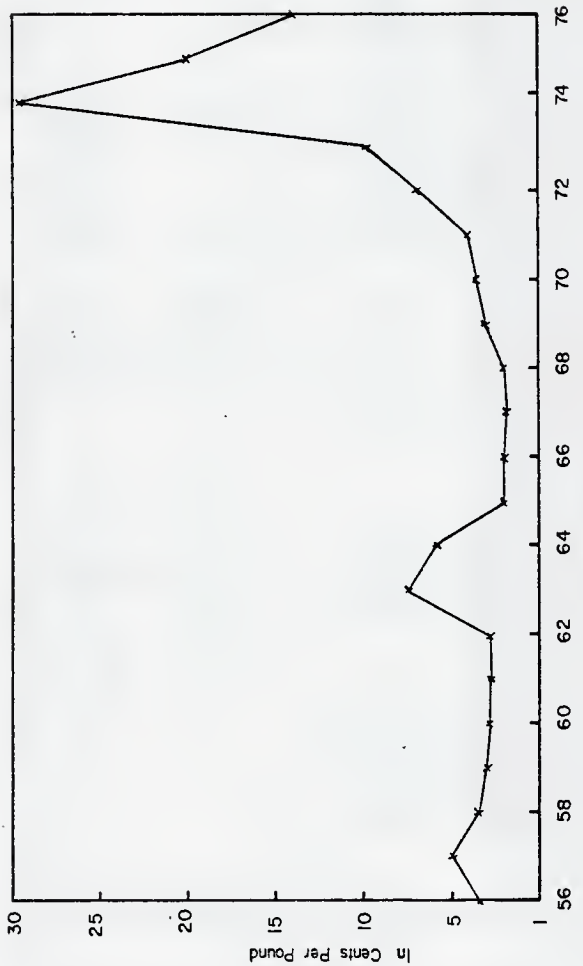


Fig. 10. Fluctuating World Price of Raw Sugar (Troy, 1977).

28.7, and 32.5%, respectively, by the year 2000 (Cantor, 1975).

The last development worth mentioning is that both the per-capita consumption and the market share of the other caloric sweeteners (except sucrose sweeteners and corn sweeteners) has declined (Page et al., 1974).

In addition to the current developments of sweeteners discussed above, the impetus of the impending ban on saccharin, the last non-caloric sweetener available in the U.S., also affects the sweetener market trends, and spurs industry search for substitutes (Wightman, 1977).

2.2 Sugar (sucrose) substitutes

Sucrose is the oldest sweetener derived from commercially cultivated plants. Nearly all of the world's commercial supply of sucrose comes from sugar cane and sugar beets (Inglett, 1974). Sucrose has been the dominant carbohydrate sweetener for a very long time. Lately, this stable picture has begun to show unmistakable signs of change (Aminoff, 1974; Crosby,1976). The main reasons, as stated earlier, are the high and fluctuating sugar prices, the recent availability of high-fructose syrup, and the saccharin ban.

At the present time, only the starch-based glucose products have been able to conquer a significant part of the market for sweeteners (Commerford, 1974). Starch suitable for the manufacture of syrup and dextrose may come from any one of numerous plant sources, although corn is the most important native source in the U.S. (Schanefelt, 1977).

In addition to boosting the starch and non-caloric sweeteners already on the market, high sugar prices also provide a strong stimulus for the development of new sucrose substitutes (Walter, 1974). Although there are many nutritive (caloric) and non-nutritive (non-caloric) sucrose substitutes other than corn sweeteners, listing them all here is superfluous.

Here, discussions will be given only on those sweeteners that could be produced in quantity at reasonable prices if their potential uses were there.

There are four types of need for a non-nutritive (non-caloric or synthetic) sweetener. The first is for diabetics; the second is for a flavoring agent for pharmaceuticals; the third is for the obese in dieting; and the fourth is for the underfed people - the problems attending scarcity of food (Beck, 1974). Non-nutritive sweeteners that have the most potential other than saccharin and cyclamates, are:

Aspartame, L-aspartyl-L-phenylalanine methyl ester, which is a dipeptide synthesized from two naturally occurring amino acids (McCormick, 1975).

Dihydrochalcone, which is obtained by hydrogenation of chalcones obtained from their natural occurring flavanones, naringin and neohespenidin. (Inglett et al., 1969).

Other sweeteners which are naturally occurring but completely free from carbohydrates are being seriously investigated by many researchers (ven der Wel, 1974; Davis, 1975; Crosby, 1976). These sweeteners include monellin from serendipity berries, thaumatin from katemfe, and miraculin from miracle fruit.

Due to some limitations, most of the non-carbohydrate sweeteners mentioned above cannot replace sucrose completely. They do not have a preservative effect, do not provide body for syrup, candies, and baked goods, and cannot serve as yeast food (Aminoff, 1974).

Among the sucrose substitutes available, maltito (Aminoff, 1974), xylitol (Emodi, 1978) and pure fructose (Doty et al., 1975) are three promising carbohydrate sweeteners. They, particularly fructose, probably can compete with corn sweeteners.

Until recently, the use of fructose as an ordinary dietary constituent has been very limited because of its high price as compared to sucrose. A few years ago the chemists at the Finnish Sugar Company Ltd. succeeded in developing a new manufacturing process for fructose from sugar beets, and the Clinton Corn Processing Company produced high-fructose corn syrup from a two-step enzymatic conversion of corn starch (Nikkila, 1972; Davis, 1975). These have made it possible to prepare fructose on an industrial scale at a reasonable price.

2.3 Fructose production from starch

Starch, the major product of the corn wet milling industry, is used as a raw material for the various corn sweeteners. More than 90% of the starch used in the United States comes from corn (Inglett, 1970). By 1974, there were three main types of corn sweeteners on the market: corn syrup (glucose syrup), malto dextrins, and dextrose (Commerford, 1974).

Although dextrose and corn syrups have unique properties of their own, they suffer in competition with sucrose because of their lower sweetness value. Dextrose is only 0.74 times as sweet as sucrose, as indicated in Table 7. The starch industry has recognized the desirability of developing sweeter products in order to further expand their markets in sweetened foods. Isomerization of glucose to fructose was the most obvious method for achieving this (Casey, 1976).

The historical development of fructose-containing corn syrup was described in detail by Newton et al. (1974). Some of the most important items are reviewed below.

In 1812, Kirchoff published the first report of the production of sweet starch hydrolyzates by acid-hydrolysis. This method was used through 1940.

In 1940, Dale and Langlois discovered the acid-enzyme dual conversion method. This was the first improvement for corn syrup, and replaced the low sweetness and bitter taste that were typical of the corn syrup made from the acid-hydrolysis method. In 1950, the enzyme glucoamylase was commercialized to produce high-dextrose corn syrup with a dextrose equivalent range of 95 to 97 DE (dextrose equivalent).

In 1957, Marshall and Kooi reported the isolation of an enzyme for isomerizing glucose to fructose. Although numerous processes have been discussed in the literature, the basic process for producing high-fructose corn syrup in the U.S. is described in U.S. patent 3,616,221, issued to Takasaki and Tanable in 1971. The finished high-fructose corn syrup contains 45 to 50% fructose and 50 to 55% glucose.

In 1975, the Clinton Corn Processing Co. earned the 1975 IFT Food Technology Industrial Achievement Award for its development of a process for producing high-fructose corn syrup (Isomerose) using the immobilized enzyme technology (Mermelstein, 1975). This process has been successfully applied in actual commercial operation. Typical high-fructose corn syrup (HFCS) contains 42% fructose, 50% dextrose, and 8% other polysaccharides (Henry, 1976).

Much research is currently in progress to produce corn syrup of even higher fructose content, and even crystalline fructose.

2.4 Fructose production from sucrose

Fructose and glucose have been known as the "siamese sugar twins", which are the major components of sucrose (sugar) from sugar beet or sugar cane. According to Doty et al. (1975), early industrial methods for the production of pure fructose were based on the principle demonstrated in 1847 by the discoverer of fructose, Dubrunfaut. This method was taken

as the most desirable one for further investigation and use as a practical pilot-plant method. During the 1950's, the chemistry of the process was essentially one of inverting sugar solutions by acid, neutralizing the inverted solutions with a base, precipitating the fructose with calcium oxide, recovering the fructose from the precipitated calcium fructosate, and finally purifying, concentrating, and crystallizing the recoverable fructose (Rohrman, 1950).

Most sucrose is sold in the form of pure sugar crystals. However, about one third of the industrial sugar in the United States is handled as a liquid product. Most liquid sugar is partially or wholly inverted, i.e., the sucrose is hydrolyzed into its two component sugars, D-glucose and D-fructose (Casey, 1978).

The individual mono- and disaccharides have very similar chemical and physical properties. To separate them from each other out of inverted sugar solutions has been difficult. Selective oxidation of glucose to gluconic acid leaving fructose intact, or selective precipitation of calcium-fructosate leaving glucose intact is inherently costly and yield-sensitive (Aminoff, 1974).

During the past several years, the world's leading fructose producer-the Finnish Sugar Co., Boehringer, Roquette Freres has developed technologies by which the direct separation of glucose and fructose from inverted sugar is carried out chromatographically in ion-exchange columns (Doty et al., 1976). These high-yield processes permit economical, large-scale production of fructose.

3. Comparison of Fructose Production from Jerusalem Artichokes, Corn, Cane and Beets.

3.1 Economic considerations

The production of fructose from Jerusalem artichokes (inulin), corn (starch) and cane and beets (sucrose) has been discussed previously. To investigate the future opportunities for the production of fructose from Jerusalem artichoke tubers, it is desirable to review the economic background of the sucrose sweetener industry and corn sweetener industry.

The world production of raw sugar has increased sharply since 1953, when it was about 34 million tons, rising to about 82 million tons in 1976, as shown in Fig. 11 (Troy, 1977). This corresponds to approximately a 2.5-fold increase. Figure 11 also shows world sugar consumption.

According to the opinion of Product Development Laboratory, Applied Sugar Laboratories, Inc., a Division of Sucrest Corp., Brooklyn, N. Y., the price of raw sugar will increase when the production of raw sugar is below the consumption level for 2 or more years. When world sugar stock was maintained at about 25% above world consumption, prices remained fairly steble (Troy, 1977). Ups and downs in sugar prices are to be expected in future years, but the price is not expected to return to its historical levels for any extended period of time (Anonymous, 1976).

The per-capita consumption of sugar is an excellent indicator of the economic advancement of a country. The per-capita consumption of sugar in the United States has been around 110 lb. per year since 1975, only 11 lb. per year in India and 9 lb. per year in China (Pangborn, 1975). The supplies of sugar depend considerably on imported cane, and thus sugar prices depend largely on the fluctuating world sugar prices (Rosenzweig, 1976).

To meet this enormous end growing demand, there is a strong incentive to have a home-based sugar industry. The most dramatic change has been in corn syrup, and the most dramatic development of all has been the

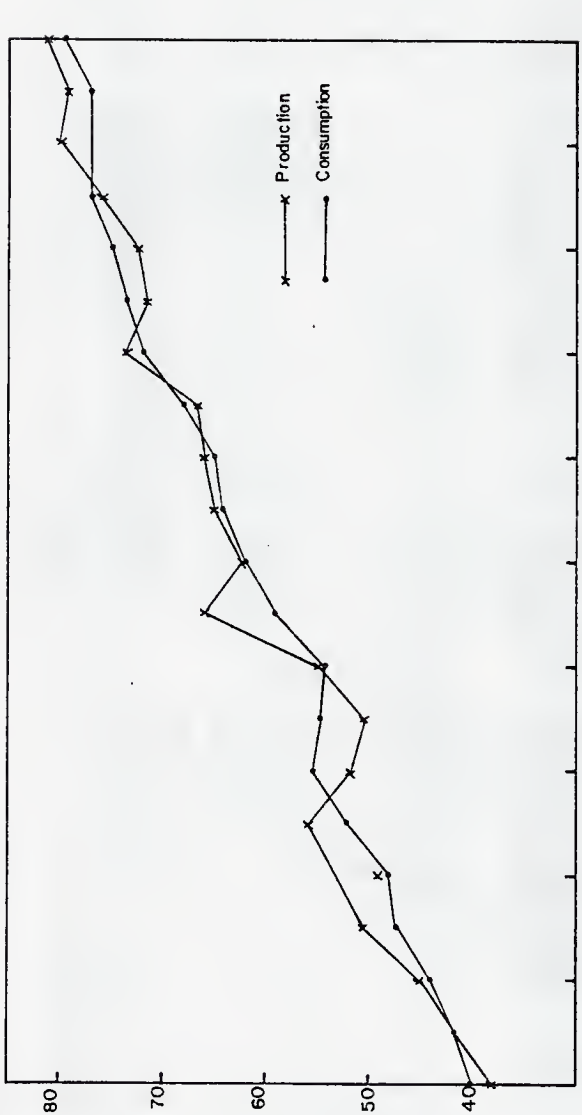


Fig. 11. World Sugar Production and Consumption (Troy, 1977).

production of high-fructose corn syrup (Casey, 1978). Predictions are that as the world demand for sugar rises, high-fructose corn syrup will fill the growing need for sweeteners in the U.S., because of its basically lower cost (Anonymous, 1976). Another development may be the production of crystalline fructose from corn-derived sweeteners, a more economical source than sucrose. This is also due to the availability of corn, the domestic, plentiful, and cheap crop (Crocco, 1976).

The operation of a semi-commercial factory for fructose production from Jerusalem artichoke tubers at Iowa State University (1931 to 1933), proved that fructose can be produced from Jerusalem artichoke tubers at a cost equal to that of cane and beet sugar, if Jerusalem artichoke can be produced in quantity (McGlumphy, 1933). Chubey et al. (1974) recommended Jerusalem artichoke, which had been successfully produced in Western Canada, as a new crop for the prairies. Also, Yamazaki (1954) in Japan, investigated the production of fructose from Jerusalem artichoke tubers on a commercial-scale and concluded that the cost of the raw material, Jerusalem artichoke, was the only problem which had to be solved.

3.2 Agronomic considerations

The agricultural advantages and disadvantages of Jerusalem artichoke as a source of fructose have been discussed previously. It is interesting to compare other plants used for fructose production from the agronomic standpoint. Corn and beets are the two vigorous competitors of Jerusalem artichoke at the present time in the United States. The comparison is summarized as follows:

a. The Jerusalem artichoke is adapted to many types of soils, even poor soils. It will grow almost anywhere in Central and North America (Haber et al., 1941; Dorrell et al., 1977). Corn can also

be grown in a wide range of soils; however, sandy soils are less suitable, and clay soils give low yields (Matz, 1969). Sugar beets require a soil texture intermediate between light and beavy, with a good structure and considerable humus (McGinnis, 1969).

b. Common varieties of Jerusalem artichoke can be grown as any staple crop and will withstand frosts. The growing season extends mucb further into the winter than that of other root crops (Sebert, 1974). The typical corn climate can be found in regions with climates ranging from temperate or subtropical to a transition marine-continental. The typical beet climate can be found in regions with climates ranging from temperate to cold area. Both corn and beet need a long frost-free period, and rainfall (McGinnis, 1969; Shaw, 1977).

c. The period of cultivation is short for Jerusalem artichoke, because its abundant growth kills the weeds and prevents the soil from baking (Masson, 1973). On the other hand, much time is needed in tbe cultivation of beets and corn to rid themselves of weeds and avoid the baking of soil (Dicke, 1977; Mariller, 1943).

d. The plant and tubers of Jerusalem artichoke are reported to be almost completely free from injury by plant diseases and insects (Allemand, 1971; Masson, 1973; Sebert, 1974). However, there are many plant diseases and insects that are destructive to corn (Ullstrup, 1977; Dicke, 1977). Sugar beets are attractive hosts to certain nematodes (McGinnis, 1969).

e. The yield of Jerusalem artichoke responds well to moderate fertilization, but the sugar yield is not affected significantly (Dorrell et al., 1977). On the other hand, sufficient lime,

phosphates, nitrogen, and traces of various inorganic substances are necessary for normal growth of the sugar beets (McGinnis,1969). Fertilizer is also necessary for the production of corn (Matz, 1969).

f. Large yields of inulin-containing tubers of Jerusalem artichoke are easily obtained. The yield of tubers per hectare is up to 23 tons in Japan (Yamazaki, 1954), 32 tons in Nebraska, U.S.A. (Martin et al., 1957), 45 tons in the Netherlands (pilnik et al., 1976), 50 tons in Manitoba, Canada (Dorrell et al., 1977), and 65 tons in France (Marilla, 1943). These are about 3-7 times the harvest of corn (Larson et al., 1977).

g. Once planted, the Jerusalem artichoke tubers continue to multiply without replanting. Sebert(1974) visited a farm where the original planting had been done more than 50 years ago. The family moved away, but the Jerusalem artichoke was still holding its own. On the other hand, corn and sugar beets need to be replanted every one or two years (McGinnis, 1969; Craig, 1977).

h. Jerusalem artichoke tubers can be left in the ground all winter, or covered with a layer of earth immediately after being dug. The longer they remain underground, the better the taste (Reay, 1969; Criner, 1970). However, the ratio of fructose to reducing sugar will decrease (Dorrell et al., 1977). On the other hand, corn and sugar beets have to be harvested before the first frost (Matz, 1969; McGinnis, 1969).

i. One of the major problems of Jerusalem artichoke is the difficulty involved in harvesting, but the present-day advanced mechanical harvestors (e.g., the four-row uniharvestor for corn or other crop

plants) might solve this problem.

j. Unlike the beet sugar industry, which is essentially a one product industry (Cantor, 1974), the tubers, stems, and leaves of Jerusalem artichoke can be used. This is also the case for corn. The utilization of corn is very diverse; e.g., corn oil, cornmeal and popcorn (Watson, 1977).

The low yields of Jerusalem artichoke tubers imply that little attention and little effort has been made to improve the plant in the United States. However, it has already been shown how well the Jerusalem artichoke responds to scientific treatment (Weick, 1943; Martin et al., 1957). It should be remembered that the superior qualities of the sugar beet and corn are the result of selection and propagation for more than a century (Sprague, 1977; McGinnis, 1969). The Jerusalem artichoke is a potential sweetener crop plant that could very well compete with beets and corn.

3.3 Processing considerations

The Jerusalem artichoke has been investigated several times in this century as a raw material for fructose production, but each time various difficulties associated with its cultivation and processing, and competition from sucrose discouraged commercial fructose production. With the availability of a variety of the present day technology, the idea of fructose production from Jerusalem artichoke should be reexamined. First of all, the fructose can be produced from a less complex starting material, (i.e. the polysaccharide inulin) than from corn syrup or inverted sugar solutions. The process avoids the glucose isomerase conversion step since inulin, the polyfructosan, can be obtained directly from Jerusalem artichoke tubers grown as a crop; therefore, it reduces the cost of producing fructose.

Advanced production methods, such as waste heat utilization, new

crystallization technology, and decoloration method, have been extensively applied to reduce operating costs involved in sugar refining (Cantor, 1974). The application of these advanced production methods can be exploited to reduce the cost of commercial-scale production of fructose from Jerusalem artichoke tubers. The recommended process for production of fructose is as follows: Slicing raw Jerusalem artichoke tubers into cossettes (Profitt, et al., 1936), drying these artichoke cossettes for storage (McGlumphy, 1931), extracting inulin and other polyfructoses with hot water in a counter-current diffusion battery (Yamazaki, 1954), saccharifying to fructose by enzyme or mild acid treatment (Barker, 1976), refining by vacuum filtration, carbon, and ion-exchange (Mermelstein, 1975), aud concentrating the refined fructose syrup into pure crystalline fructose (Barker, 1976). As mentioned previously, the concentration of extracted polysaccharide (inulin) or converted fructose obtained by hydrolysis can be accomplished by membrane ultrafiltration or reverse osmosis membrane filtration (Fan, 1976).

OTHER UTILIZATIONS OF JERUSALEM ARTICHOKE

The United States corn-sweetener industry flourished largely because the cost of its raw material was buffered by a huge crop raised specifically for animal feed (Cantor, 1974). The use of Jerusalem artichoke tubers as food and feed is fairly well known in Europe, but insignificant in America (Shoemaker, 1927). If a huge Jerusalem artichoke crop were raised for feed and food, this would not only lower its cost as a raw material for fructose production, but also give opportunities to workers in the feed and food industries. In addition, the economic viability of such a crop could well depend upon utilization other than feed and food, for example, alcohol production from the tubers of Jerusalem artichoke (Prescott. 1940). The utilization of other parts of this plant is also worth considering.

1. As a Source of Food and Feed

The possibilities of the Jerusalem artichoke as a commercial source of sugar has been discussed in an earlier section. However, it would also be well to point out the value of the plant for stock feed and other food products.

As a table vegetable, Jerusalem artichoke tubers can be prepared in several forms. They can be boiled, fried, baked, pickled, salted, and eaten raw alone, or mixed with fruit or vegetables for a salad supreme (Sebert, 1974). Cooked Jerusalem artichoke tubers resemble cauliflower in taste. If eaten raw or cut up in salads, their texture is waterchestnut-crisp and their flavor nut-like

Although the Jerusalem artichoke tubers are low in calories and have no starch, they contain some vitamins and nutrients - especially potassium and thiamine (Masson, 1973).

The Jerusalem artichoke tubers make excellent livestock feed. Milk cows fed these tubers are reported to produce more cream; raw tubers fed

to poultry are reported to improve egg production and size (Natural Resources Intelligence Service, 1929). Stalks and leaves of Jerusalem artichoke are good for animal forage since they are smooth, tender, and less coarse than corn or sunflower (Allemand, 1971).

2. As a Raw Material for Alcohol

As stated by Calvin (1977), "No longer can Americans rely on any single resource for the bulk of their energy, as they have periodically throughout their history - first with wood, later with coal, and today with oil." The energy shortages and the dramatically rising prices for fuel since 1973 have created much interest in finding new energy sources, such as nuclear energy, solar energy, and fuels from biomass (see, e.g., Buswell, 1978; Calvin, 1978; Lipinsky, 1978).

Fermentation to produce alcohol - not only a fuel for men and machines but also a chemical raw material - from agricultural products, particularly crop plants, is almost competitive with synthetic alcohol from petroleum or petroleum fuels. In the U.S., about 475 million acres are classified as cropland, which undoubtedly is a potential source of energy (Miller, 1973). Furthermore, a sizeable portion of this cropland is unused, where Jerusalem artichoke can be planted.

2.1 Production of industrial alcohol

Since the advent of the reciprocating engine, alcohol has been considered as a possible fuel. Bridgeman (1936) published a paper entitled "Utilization of Ethanol Gasoline Blends as Motor Fuel". Pure alcohol has a high octane number (on the order of 106) and a significant blending value for upgrading gasoline. The power output of an engine is also increased as the alcohol content of the fuel is increased.

Prior to World War II, large quantities of alcohol were used as a

motor fuel in Europe. During the war, the largest quantities of alcohol were used in the manufacture of explosives and other materials of war. Since the end of World War II, the use of alcohol as a motor fuel has declined to almost zero (Scheller, 1974).

There was a time in this country when yeast fermentation of a variety of fermentables was the principal method of obtaining industrial alcohol. Fig. 12 shows industrial alcohol production in the United States for the past thirty years (Calvin, 1976). Before World War II, fermentation to alcohol was the main source. Currently, the major portion of industrial alcohol is made from ethylene, which is the raw material for most of the chemicals in use industrially (polyester, nylon, polyurethane foam, glycol and polyglycol, etc.). It is a byproduct of petroleum refining techniques, not from renewable fermentables.

Today with the "energy crisis" and automotive fuel shortages, interest has once again turned to making ethylene from alcohol. Agricultural alcohol has certain attractive features associated with it, not the least of which is that it represents a renewable energy source. Raw materials, such as sugar cane and corn, are available in large quantities at a relatively low cost (Lipinsky, 1978).

Alcohol fermentation using starch from cereal grains (wheat, corn, sorghum, etc.) and sucrose from sugar cane or molasses is technically feasible (Monier-Williams, 1922). Basically, a bushel of wheat, sorghum, or corn will yield 2.6 to 2.7 gallons of anhydrous alcohol (Miller, 1974). Practically, it takes twelve pounds of sugar to create one gallon of alcohol. The cost of one gallon of alcohol is equal to the cost of the raw materials, plus about 20¢ for processing (Calvin, 1976).

2.2 Alcohol production from Jerusalem artichoke

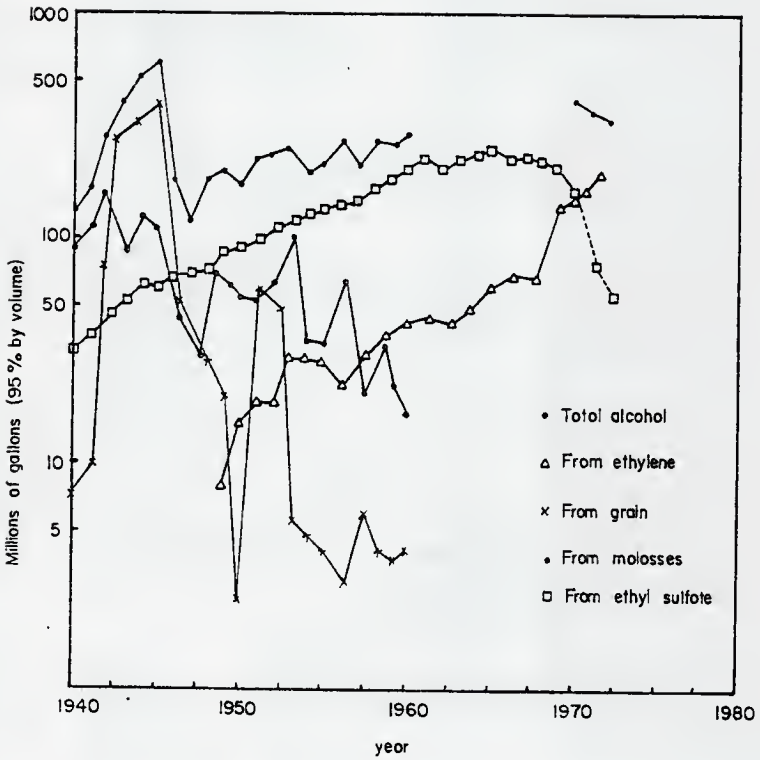


Fig. 12. Industrial Alcohol Production - by Material Used August, 1971 (Calvin, 1976).

The Jerusalem artichoke was recognized by Wiley et al. (1911) as a possible source for the manufacture of alcohol almost seventy years ago. According to Underkofler et al. (1937), the tubers were used in a few early small-scale manufacturing operations in Germany and in France.

During the period 1935-1945, interest in the fermentation production of alcohol grew rapidly because of the need of war (Underkofler et al., 1939; Prescott, 1940; Calvin, 1976). The high yield of Jerusalem artichoke attracted considerable attention as a possible new material for alcohol production. Comparison figures of the yield of some crops are shown in Table 10 (Monier-Williams, 1920; Prescott, 1940; Inglett, 1975; Calvin, 1977). The first plant in the United States designed solely for the production of alcohol from domestic farm crops began operation at Atchison, Kansas, in 1936 (Fulmer et al., 1938).

Christensen et al. (1935) were issued a U.S. patent for the production of ethyl alcohol from artichoke tubers. They developed a process of producing alcohol from unhydrolyzed artichoke tuber diffusion liquor by repeated propagation of a yeast of high fermentation capability. The yeast they used was able to convert 82 to 94 percent of the carbohydrates in Jerusalem artichoke tubers into alcohol.

Underkofler et al. (1937) compared the yields of alcohol from the fermentation of dried artichoke chips, artichoke flour, fresh artichoke mashes, and artichoke syrup (hydrolyzed and unhydrolyzed). They found the fermentation of pulpy artichoke mashes had a "heading" problem which resulted in incomplete conversion of the carbohydrates into alcohol. They also found that preliminary acid hydrolysis of the carbohydrates was not necessary for successful fermentation.

After the period of 1935-1945, alcohol could be produced from cheaper

Table 10. Comparison of Raw Materials Containing Starch or Sugar for Alcohol Production (Monier-Williams, 1920; Winton et al., 1932-1939; Prescott, 1940; Calvin, 1977).

Items	Sugar cane	Sugar beets	Wheat	Corn	Potato	Jerusalem artichoke
Moisture (%)	74.96	81.50	10.52	13.80	78.3	79.70
Protein (%)	0.58	1.75	11.87	8.90	2.2	1.48
Fat (%)	0.38	0.10	2.09	3.90	0.1	0.14
Carbohydrates (%)	23.44	15.77	73.69	74.20	18.4	17.61
Ash (%)	0.64	0.88	1.83	1.20	1.0	1.08
Average yield (metric tons/hectare/yr.)	1.22	33.0	10.0	13.0	45.0	40.0
Total fermentable carbohydrates (%)	13.0	15.0	65.0	67.0	17.5	17.0
Average yield of 99.5% alcohol (gal./ton)	15.2	22.1	85.0	84.0	22.9	20.0
Average yield of 99.5% alcohol (gal./acre)	889.0	287.0	33.0	88.8	178.0	180.0

and more abundant sources, primarily petroleum, and thus little research was performed on the production of alcohol from agricultural products, including Jerusalem artichoke.

3. As a Raw Material for Methane Gas

3.1 Anaerobic digestion of methane gas

Anaerobic digestion to produce methane gas from biomass has received renewed interest in recent years (Compere et al., 1975; Converse et al., 1975; Hein et al., 1975; Clausen et al., 1976). This interest is understandable in view of the mounting shortage of energy sources, and the increasing desire of many to develop a more self-sufficient pattern of living, especially in rural areas (Fry et al., 1973).

Fuel is simply a material which can be used to produce useful work upon combination with oxygen. This means that the material must be in a reduced form so that it can be oxidized. The most reduced carbon compound used as fuel is methane - carbon attached only to hydrogen - CH_4 (Calvin, 1976). The fuel value of methane and other major fuel gases is shown in Table 11.

In anaerobic digestion, the biomass is impregnated with large quantities of microorganisms. Here, air is excluded. Unlike aerobic oxidation, the anaerobic conversion to methane gas yields relatively little energy to the microorganisms. Thus, their rate of growth is slow, with the major portion of the degradable biomass being converted to methane gas (McCarty, 1964; Andrews, 1965; Bell, 1973). Recently, the physical separation of the process into two or more stages has been used. This permits the establishment, in each stage, of environmental conditions most suitable for each group of microorganisms involved and results in substantially higher overall reaction rates (Keenan, 1975).

Table 11. Fuel Value of Bio-gas and Other Major Fuel Gases (Fry et al.,1973)

Fuel gas	Fuel value (BTU*/ft^3)
Coal gas	450-500
Bio-gas	540-700
Methane	896-1069
Natural gas (Methane or propane-based)	1050-2200
Propane	2200-2600
Butane	2000-3400

*BTU means British Thermal Unit. One BTU is the amount of heat required to raise one pound of water from 58.5°F to 59.5°F.

The conversion of biomass to fuel gas via anaerobic digestion represents a potential solution not only to the energy problem but simultaneously to the solid waste problem.

3.2 Methane gas from Jerusalem artichoke

Little information regarding the anaerobic methane fermentation from Jerusalem artichoke is available. According to Buswell et al. (1939), a few studies were undertaken for the digestion of Jerusalem artichoke in Illinois during the early 1930's.

An important work was performed by Abbott (1933) on the digestion of Jerusalem artichoke residues from the extraction process in batch and continuous feeding experiments. The batch fermentation experiments were carried out in one-liter dark glass bottles, and the continuous feeding fermentation experiments were carried out in a seven-liter tank by continuously feeding Jerusalem artichoke residue to the tank. The data obtained from the batch experiments show that in 18 days, 82 to 87 percent of the waste was recovered as a gas containing about 50 percent methane. In one of the continuous-feeding experiments, 1078 gms (dry basis) of artichoke residues were fed to the tank and produced 557.07 liters (19.67 ft^3) of total gas; in the other 847.47 gms were fed to the tank and produced445.95 liters (15.75 ft^3) of total gas. The percentage of methane gas ranged from 50.7% to 63.2%. Thermophilic (50 -55°C) fermentation has no advantage over a mesophilic (25 -30°C) fermentation for the gasification and stabilization of Jerusalem artichoke residues.

Buswell and coworkers (1939) compared the methane gas fermentation from many sources such as corn stalks, wheat straw, manure, green corn stalks, manure and artichokes, extracted artichokes, whey and artichoke. They found that the largest volume of gas could be recovered from Jerusalem

artichoke residue pulp, and it had the greatest gas production rate among the sources. The average percentage of CH_4 in the recovered gas was 56%, and 577.9 lbs. (262.7 kg) of extracted Jerusalem artichoke residues (dry basis) produced 6,600 cubic feed of methane.

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CHAPTER 3

THE CULTIVATION OF JERUSALEM ARTICHOKE

INTRODUCTION

As indicated in the previous chapter, it has often been reported that the Jerusalem artichoke can be grown easily with little water, fertilizer and with minimum effort (see, e.g., Reay, 1969; Allemand, 1971; Masson, 1973; Mayfield, 1974). The objective of this study was to examine if it is indeed true. Another objective was to obtain a supply of Jerusalem artichoke tubers (USSR 357304) for later work.

CULTIVATION

1. Seed Tubers

The seed tubers of Jerusalem artichoke were supplied by the North Central Regional Plant, United States Department of Agriculture at Iowa State University. The origins of the seed tubers were Helianthus tuberosus USSR 274517, USSR 274518, USSR 357297, USSR 357298, USSR 357299, USSR 357301, USSR 357302, USSR 357303, USSR 357304. The USSR 357304 was planted on May 15, 1976 and harvested on October 31, 1976, in the backyard of the L. T. Fan residence, Manhattan, Kansas. The rest of the eight accessions of Jerusalem artichoke were planted on May 3, 1976 and harvested on November 15, 1976, at the Agronomy Farm of Kansas State University.

2. Crowth Mode

About 2 pounds (40 plants) of Jerusalem artichoke tubers, USSR 357304, were planted about 4 to 6 inches (10-15 cm) deep and about 12 inches (30 cm) apart.

The pictures of the full view and two single plants of the first generation were taken every third day from May 25, 1976 to October 31, 1976. The mode of growth for the full view of the first generation

Jerusalem artichoke is shown in Fig. 1, and for one single plant of the first generation is shown in Fig. 2.

From the figures, it can be seen that the leaves grew in pairs of two, oriented in the opposite direction. The plants grew rapidly to six to more than eight feet (ca. 180 cm to 250 cm) tall; they became bushy and shaggy. The flower bloomed late in the season and the blooming time was short, only about three to six weeks. The flowers, which bloomed near the top of each stalk, were exactly like small wild sunflowers, e.g., yellow daisy.

The eight accessions of Jerusalem artichoke grown at the Agronomy Farm of Kansas State University are shown in Fig. 3.

The growth of Jerusalem artichokes was nearly work-free. They were fast-growing plants. They withstood drought, frost, and almost completely resisted insects and plant diseases. No water, fertilizer, insecticide or herbicide were necessary during growth, as indicated by experienced workers (see, e.g., Masson, 1973; Mayfield, 1974; Sebert, 1974).

3. Harvesting

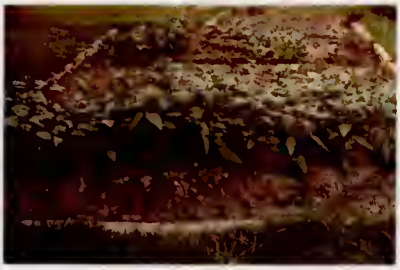
The tops of the first generation were cut and the tubers were dug after fading and dropping of the flowers. This took place five months after seeding. The harvesting problem seemed to be the most serious one since the stems are tough and woody at harvest. The tubers formed a large mass at the base of the stem, intertwined with the roots, from which they were not easily separated. However, this problem can be easily solved by present-day digging machines (Larson et al., 1977).



May 25



June 30



June 6



July 21



June 15



August 14

Fig. 1. Full View of the First Generation Jerusalem Artichoke Grown in the Backyard of Fan's Residence, Manhattan, Kansas (Fan, L. T. 1976).



Sept. 13



Oct. 31 The Harvest



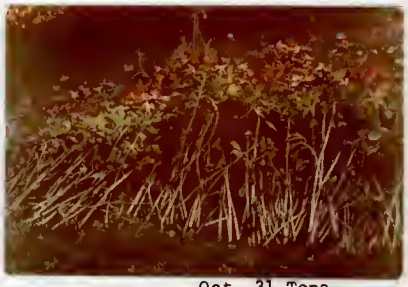
Oct. 10 The Blossom



Oct. 31 Tubers



Oct. 31 Before Harvest



Oct. 31 Tops

Fig. 1. (Cont'd).



May 25 (2 ft)



June 6 (2.5 ft)



June 15

Fig. 2. Single Plant of the First Generation Jerusalem Artichoke Grown in the Backyard of Fan's Residence, Manhattan, Kansas (Fan, L. T., 1976).



June 30

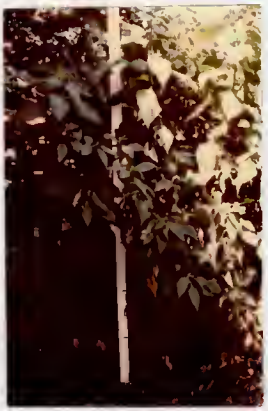


July 21 (5 ft)



Aug. 2

Fig. 2. (Cont'd)



Aug. 14 (6 ft)



Sept. 10 (6.5 ft)



Oct. 10 The Blossom

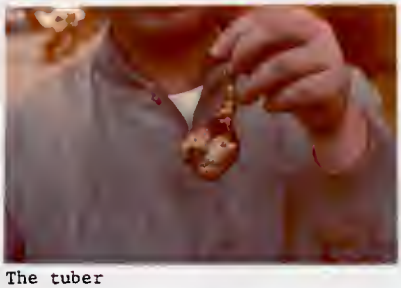
Fig. 2. (Cont'd).



Oct. 10 The flower



Oct. 31 Before harvest



Oct. 31 The tuber

Fig. 2. (Cont'd).



July 1 Full View



Oct. 2 Faded Jerusalem Artichokes

Fig. 3. Jerusalem Artichokes Grown at the Agronomy Farm of Kansas State University.

Undersized tubers of the first generation Jerusalem artichoke were left underground and germinated around the beginning of May in 1977, giving rise to the second generation Jerusalem artichoke. The growth mode of the second generation Jerusalem artichoke is shown in full view in Fig. 4. The growth mode of a single plant in the second generation Jerusalem artichoke is shown in Fig. 5.

CONCLUSION

This plant was found indeed to be productive and very easy to grow. (Small tubers of the second generation Jerusalem artichoke left underground germinated in mid-April, 1978. It is nearly full grown at the present time - July 1978).



May 5



June 8



Julu 14

Fig. 4. Full View of the Second Generation Jerusalem Artichoke Grown in the Backyard of Fan's Residence, Manhattan, Kansas (Fan, L. T., 1977).



Aug. 18



Sep. 18



Oct. 2

Fig. 4. (Cont'd).



May 5



June 1



July 14

Fig. 5. Single Plant of the Second Generation Jerusalem Artichoke Grown in the Backyard of Fan's Residence, Manhattan, Kansas (Fan, L. T., 1977).



Aug. 18



Sep. 24



Oct. 10

Fig. 5. (Cont'd).

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CHAPTER 4

PRODUCTION OF FRUCTOSE BY SIMULTANEOUS EXTRACTION AND CONVERSION OF POLYSACCHARICES FROM JERUSALEM ARTICHOKE TUBERS

INTRODUCTION

The sources from which the fructose may be derived and its peculiar properties have been reviewed in Chapter 2. Commercial production of fructose has increased for the last several years. Fructose or high fructose products are attractive alternatives to sucrose if economically feasible. High-fructose corn syrup from starch and fructose from inverted sugar have been two main starting materials for fructose production. Inulin, which is less complex than these materials, has not received much attention as a starting material for the production of fructose until very recently (Doty, 1975; Barker, 1976; Dorrell et al., 1977).

The objective of this work was to conduct two sets of experiments to evaluate the effect of sample preparation methods and the effects of extraction temperature and extraction time on the yield of fructose produced from Jerusalem artichoke tubers. Twelve varieties of Jerusalem artichoke tubers were used in this work. Their moisture and reducing sugar contents were also investigated.

THEORETICAL

Fifteen to eighteen percent by weight of the contents of Jerusalem artichoke tubers are the total sugars, 75-87% of which hydrolyze to fructose (Pilnik et al., 1976). The total sugars mainly include disaccharides (sucrose or difructose anhydride), inulides and inulin (Torchinskeya, 1968; Taniguchi et al., 1972). The arrangement of the sugar residues in these compounds is as follows (Barnett et al., 1976):

$$\beta\text{-D-Fruf 2}\left(\rightarrow 1\ \beta\text{-D-Fruf 2}\right)n \rightarrow 1\alpha\text{-D-Glup}$$

where the (Fruf) is the fructofuranosyl group or residue, and the (Glup) is the glucopyranose residue, and n may be any number, e.g., zero for sucrose, about 35 for inulin, and between zero and 35 for an inulide. The fact that each of these compounds contains only one terminal glucose unit (D-Glup) renders the hydrolysates of these compounds to contain only small amounts of glucose of less than 20% (Jefford, 1960).

All of these compounds produce fructose as a major end product when completely hydrolyzed. The conversions of these compounds to fructose are as follows (see, e.g., McDonald, 1946; Honeyman, 1962; McDonald, 1969):

$$\underset{\text{sucrose}}{C_{12}H_{22}O_{11}} + H_2O \xrightarrow{H^+} \underset{\text{fructose}}{C_6H_{12}O_6} + \underset{\text{glucose}}{C_6H_{12}O_6}$$

$$\underset{\substack{\text{difructose}\\ \text{anhydride}}}{C_{12}H_{22}O_{11}} + H_2O \xrightarrow{H^+} \underset{\text{fructose}}{C_6H_{12}O_6} + \underset{\text{fructose}}{C_6H_{12}O_6}$$

$$\underset{\substack{\text{inulides or}\\ \text{inulin}}}{(C_6H_{10}O_5)_n} \cdot H_2O + H_2O \xrightarrow{H^+} (n-1)\ \underset{\text{fructose}}{C_6H_{12}O_6} + \underset{\text{glucose}}{C_6H_{12}O_6}$$

Chubey et al. (1974) determined the content of total reducing sugar, fructose and glucose of Jerusalem artichoke tubers and found that a high tuber yielding Russian strain, on a wet basis, had a mean reducing sugar content of 16.9%, of which 76.8% was fructose and 13.5% was glucose.

The sample preparation methods affect the yield of reducing sugar (mainly fructose) from Jerusalem artichoke tubers (Proffitt et al., 1936). In addition, the extraction temperature and extraction time affect its rate and yield (McGlumphy et al., 1931; Dykins et al., 1933).

EXPERIMENTAL

The Jerusalem artichoke tubers for the reducing sugar production experiments were cultivated in the Agronomy Farm of Kansas State University and the backyard of Dr. L. T. Fan's house. The origin, supplier, and cultivation of this plant have been described in Chapter 3. The accessions included Helianthus tuberosus USSR 274517, 274518, 357297, 357298, 357299, 357301, 357302, 357303, and 357304. The reducing sugar content of Jerusalem artichoke tubers obtained from three different places, Minnesota, California, Kansas were also evaluated.

The materials used and the procedure employed for the production of reducing sugar from Jerusalem artichoke tubers are described below. The effect of the different sample preparation methods, extraction times and temperatures have also been examined.

1. Reagents and Apparatus

The reagents used were:

a. D-Fructose standard solution (Fisher Scientific Company);

b. Liquified phenol, approximate 88%, specific gravity 1.075;

c. DNS Reagent, prepared by mixing 1416 ml of distilled water, 10.6 grams of 3.5-dinitrosalicylic acid, and 19.8 grams of NaOH, followed by addition of 306 grams of Rochelle salts, 8.8 ml of liquefied phenol, 8.3 grams of sodium-metabisulfite;

d. 1% (w/v) phenophthalein, prepared by adding 1 gram of phenophthalein to ethanol to 100 ml;

e. 0.1N hydrochloric acid;

f. Saturated neutral solution of lead acetate.

The apparatus and equipment used were:

a. Spectochlorimeter 600 (New Brunswick Scientific Co., Inc., N.J.);

b. New seven-step centrifuge (International Clinical Company);

c. pH meter (Fisher Scientific Company);

d. 250 ml suction flask with Büchner funnel;

e. Water bath with heating and agitation system;

f. Series of 100 ml Erlenmyer flasks;

g. Series of 100 ml volumetric flasks;

h. Series of pipets delivering 1.0, 2.0, 3.0, 5.0 and 10.0 ml.

2. Procedure

2.1 Sample preparation

10-gram samples were obtained from a washed Jerusalem artichoke tuber, which was sliced, cubed or ground. In the slicing method, a tuber was sliced to a thickness of approximately 1/4" (63.5mm), 1/8" (31.8mm), or 1/16" (15.9mm), and Jerusalem artichoke chips with a diameter of approximately 1" (254mm) were formed. In the cubing method, the unused portion of the same tuber was cut into cubes, each with dimensions of approximately 1/2" x 1/2" x 1/2" (127mm x 127mm x 127mm), 1/4" x 1/4" x 1/4" (63.5 mm x 63.5mm x 63.5mm), or 1/8" x 1/8" x 1/8" (31.8mm x 31.8mm x 31.8mm). In the grinding method, the unused portion of the same tuber was ground as fine as possible by an "Osterizer" blender.

2.2 Extraction and conversion

Two procedures were used to extract the sugar from tubers. The procedure employed in studying the effect of sample preparation method on the yield of reducing sugar is described below.

A treated 10-gram sample was placed in a 100 ml Erlenmyer flask, 2 grams of calcium carbonate $CaCO_3$ and about 40 ml of water were added to the flask, mixed thoroughly, covered with a steel cap loosely, heated by partially immersing the flask in a water bath at 80°C for 1 hour and then cooled to room temperature. A 250 ml suction flask with a Whatman No. 40 filter paper

with a diameter of 7 cm was used to filter the contents of flask. Additional 20 ml of H_2O were used to wash the residue on the filter paper, and finally the residue was pressed to extract as much sugar as possible.

The procedure employed in studying the effects of extraction duration and temperature on the yield of reducing sugar was essentially the same as the procedure described above. However, a small change was made in that the samples were cooled rapidly under running water after the heating and were filtered immediately because the preliminary experiments with 1/16" sliced Jerusalem artichoke tubers indicated that if the sample was cooled slowly after the heating to room temperature overnight, most of the sugars could be extracted even without heating.

The extract in each flask was transferred to another 100 ml volumetric flask, the original flask was rinsed with water and the rinsings were added to the 100 ml volumetric flask. 2 ml of a saturated neutral solution (pH = 7) of lead acetate, $Pb(C_2H_3O_2)_2 \cdot 3H_2O$, were added to each flask to clarify or deproteinize the extract. Water was added to the mark of 100 ml, and the solution was mixed. The lead precipitate was removed by centrifuging in a New Seven-Step Centrifuge at 1500 rpm for 10 minutes, and the excess lead was precipitated by adding 2 ml of a 3% (w/v) sodium carbonate solution to the supernatant and continuing centrifuging for an additional 5 minutes.

The clarified solution of each flask, which was slightly basic, was acidified with hydrochloric acid to bring its pH to 1.5 and was allowed to stand in a water bath at 80°C for 1 hour. The hydrolyzed Jerusalem artichoke extract was neutralized with sodium hydroxide and then made up to 100 ml by adding water. Aliquots were removed and diluted to a suitable volume for the determination of reducing sugar.

To study the effect of temperature and duration of extraction, the sliced samples were used and experiments were carried out at three different temperature levels of 65°, 80°, and 95°C for four different periods of 30, 60, 90, and 120 minutes. For comparison, an additional experiment was carried out by leaving a sliced sample in a flask maintained at room temperature for 60 min.

3. Analytical Method

As mentioned previously, the reducing sugars in Jerusalem artichoke tubers are mainly D-fructose and D-glucose. 3.5-dinitrosalicylic acid reagent was used for determination of reducing sugar. It has been known that this reagent is much more suitable for a number of fructosans (inulins, levans, and irisins) than other carbohydrates, for example, starch (Bell et al., 1952).

The following DNS procedure was adopted for determination of reducing sugar (Miller, 1959):

From preliminary tests it was found that the sample should contain 0.2-0.4 mg of fructose per ml. Three ml DNS Reagent were added to a 1 ml sample in a test tube. The mixture was placed in boiling water for 5 minutes and then cooled to room temperature, and poured into a colorimeter tube for the determination of reducing sugar by comparison with the standard curve using a Spectrocolorimeter 600.

0.1 mg/ml to 0.5 mg/ml standard fructose solutions were prepared and then reducing sugar content was determined by the same DNS method. A standard curve, shown in Fig. 1 was constructed. The figure shows an excellent linear relationship between the absorbance and the fructose concentration in the range of 0 and 0.5 mg/ml for the transmittance at 550 nm.

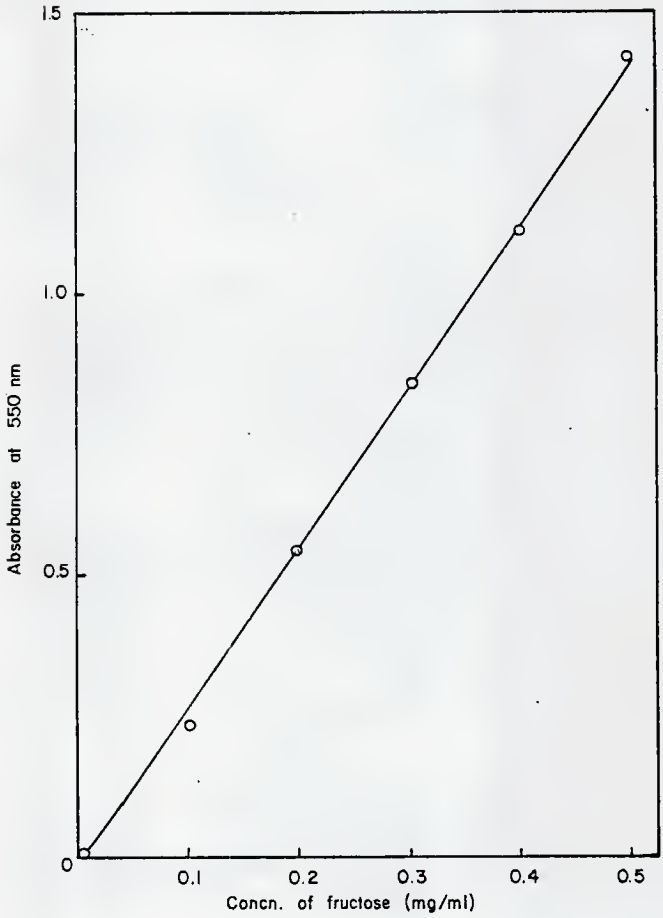


Fig. 1. Standard Curve of DNS Method for Determining Reducing Sugar.

The moisture content of Jerusalem artichoke tubers was determined as follows: Tubers were cut into quarters; thin slices were taken from the cut surfaces; samples with a fresh weight of 2-5 grams were dried in oven at 105°C for 24 hours. The weight reduction at the end of this period was taken as the moisture content of the sample because a further 24 hours drying reduced the weight by only 10-20 mg.

RESULTS AND DISCUSSION

The experimental results tabulated in Tables 1 through 3 are expressed in terms of grams of reducing sugar per 100 grams of fresh Jerusalem artichoke tubers.

The moisture and reducing sugar contents of twelve varieties of Jerusalem artichoke tubers are given in Table 1. The weight of reducing sugar per 100 grams of fresh tubers ranged from 14.9 grams to 22.3 grams, and the average was 18.1 grams. Notice that the reducing sugar content in different varieties vary widely.

Table 2 contains the results of the study on the effect of different sample preparation methods on the yield of total reducing sugars. In general, the slicing method gave a higher yield than the cubing method. Slices of approximately 1/16" (15.9 mm) thick and approximately 1" (254mm) in diamter had the highest yield. Theoretically, the grinding method should give a better yield of reducing sugars than the slicing method; however, in one of the runs from the slicing method (sample 3), the yield of reducing sugar was more than that obtained from the grinding method. The reason was probably due to the fact that many small pieces of crushed Jerusalem artichoke tubers containing appreciable amounts of juice were retained in the knife and lost prior to treatment in the grinding method.

Table 1. Moisture and Reducing Sugar Contents of Twelve Jerusalem Artichokes

Variety or Assession No.	Moisture (g/100g fresh tubers)	Total Reducing Sugar (g/100g fresh tubers)
USSR 274517	73.71	22.3
USSR 274518	77.10	19.3
USSR 357297	80.20	16.1
USSR 357298	75.20	19.9
USSR 357299	80.27	16.2
USSR 357301	80.90	17.6
USSR 357302	74.53	21.1
USSR 357303	73.50	21.3
USSR 357304	78.50	17.3
California	82.02	14.9
Minnesota	80.29	15.9
Kansas	79.17	16.5

Table 2. Effect of Sample Preparation Methods on the Yield of Total Reducing Sugar*

Sample No. (USSR 357304)	Sample Preparation Methods	Total Reducing Sugar (g/100g fresh tubers)
1	1/4" slices (Dia. 1")	15.88
2	1/8" slices (Dia. 1")	16.95
3	1/16" slices (Dia. 1")	17.65
4	1/2" x 1/2" x 1/2" cubes	13.13
5	1/4" x 1/4" x 1/4" cubes	15.10
6	1/8" x 1/8" x 1/8" cubes	16.21
7	ground particles	17.02

*Samples were extracted at a temperature of 80°C for one hour, and hydrolyzed at a temperature of 80°C and a pH of 1.5 for one hour in a water bath.

Table 3. Effects of Extraction Time and Extraction Temperature on the Yield of Reducing Sugar

Sample No. (USSR 357304)	Extraction temp., °C,	time, min.	Total Reducing Sugar (g/100g fresh tubers)
1	room temp.,	60	1.20
2	65	30	11.08
3	65	60	11.96
4	65	90	13.01
5	65	120	14.28
6	80	30	16.68
7	80	60	17.11
8	80	90	16.31
9	80	120	15.85
10	95	30	17.02
11	95	60	15.99
12	95	90	15.40
13	95	120	14.91

The results of the study on the effects of extraction temperature and extraction time on the yield of total reducing sugars are given in Table 3. The results show that the extraction temperature of 80°C and extraction time of 60 minutes gave the highest yield of reducing sugars, and the rate of production of reducing sugars was slow at the extraction temperature of 65°C. The prolonged heating at a high temperature reduced the yield of reducing sugars.

CONCLUSION

The results of this investigation indicate that the contents of reducing sugar range widely among different varieties of Jerusalem artichoke tubers. This implies that plant breeders can probably develop varieties with high sugar contents.

It was found that the sample preparation method affects the yield of reducing sugar (fructose) appreciably. The slicing method gave the best yield of reducing sugar and the grinding method gave the second best yield in this work. The combination of the extraction temperature of 80°C and the extraction time of one hour resulted in the maximum yield of reducing sugar.

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CHAPTER 5

PRODUCTION OF FRUCTOSE BY CONVERSION OF EXTRACTED POLYSACCHARIDES FROM JERUSALEM ARTICHOKE TUBERS

INTRODUCTION

Although considerable information is available concerning the chemistry of hydrolysis of pure inulin (see, e.g., Hibbert et al., 1931; Heilbron, 1936; McDonald, 1946), very little has been reported regarding the conversion of the fructose-containing polysaccharides (inulin) of Jerusalem artichoke tubers (Dykine et al., 1933). Jackson et al. (1926) seem to be the first to study the conversion of Jerusalem artichoke extract, and they indicated that the rate of hydrolysis of inulin by acids was essentially a function of pH at a given temperature. McGlumpy et al. (1931) experimentally found that time, temperature of reaction during hydrolysis, hydrogen-ion concentration of the Jerusalem artichoke extract, and the concentration of extract were the important factor affecting the rate constant. They found that there was an insignificant loss of fructose at temperatures up to 80°C, pH values down to 1.12, and treatment time of 60 minutes.

Dykins et al. (1933) also confirmed that the rate of hydrolysis of the Jerusalem artichoke extract largely depended on the pH, reaction time, and temperature. They determined the velocity constants under four sets of conditions with reaction temperatures ranging from 80°C to 130°C, reaction time ranging from 20 minutes to 60 minutes and the pH values ranging from 1.98 to 4.56 by assuming that the hydrolysis reaction followed the course of first-order reaction. However, they did not specifically determine the activation energy. They also indicated that an extract of about 38 percent solid

content was most satisfactory for Jerusalem artichoke syrup production.

The primary objective in this work was two-fold. The first was to determine the optimal reaction conditions so that the results can be used for an economic analysis of the process. Studies were made using various concentrations of the acid at different temperatures and for different times. The second was to determine the kinetics of the inulin to fructose reaction, since the rate of reaction is necessary to determine the volume of the reactor for fructose production.

GENERAL CONSIDERATION

To pursue this investigation, it was necessary to determine the independent variables involved and the range over which they should be studied. From the literature survey and preliminary experiments, the variables that affect the yield of reducing sugar from the Jerusalem artichoke extract and the ranges of these variables were found; they are listed below:

(1) pH of the extract. The rate of hydrolysis is a strong function of the extract and the fructose is unstable below a pH of 1.00 (Jackson et al., 1926; McGlumphy et al., 1931; Dykins et al., 1933). Preliminary experiments indicated that the yield of reducing sugar rapidly decreased at a pH above 3.00, a temperature of 80°C, and a treatment time of 60 minutes. Therefore, pH was varied from 1.25 to 3.00.

(2) Temperature. Upon prolonged heating, decomposition of the reducing sugar became apparent at a temperature of 90°C. At temperatures below 50°C, the rate of production of the reducing sugar was very slow. Therefore, the temperature was varied from 50°C - 90°C.

(3) Time. During preliminary runs, it was noted that the hydrolysis was almost complete within 2.5 hours for pH between 1.25 - 2.00. Therefore, the reaction period was varied from 0 to 2.5 hours.

(4) Concentration of the extract. The non-sugar material of the raw Jerusalem artichoke has a marked influence upon the acidity of the extract. It has been reported (Eichinger et al, 1932) that the higher the percentage of total solids in the extract, the higher the amount of acid required. To minimize errors which can be produced from differences in methods of preparation of Jerusalem artichoke extract, all determinations were carried out on the same extract, and hence the effect of this variable was not investigated.

EXPERIMENTAL

The Jerusalem artichoke came from the backyard of L. T. Fan's house. The crop was planted on May 15, 1976 and harvested on October 31, 1976. The origin of the seeds was Hilianthus tuberosus USSR 357304. The supplier has been mentioned in Chapter 3.

The materials, facilities and procedure employed were essentially identical to those given in the preceding chapter. They are briefly described below.

1. Reagents and Apparatus

   Reagents: the same as those listed in Chapter 4.

   Apparatus: The same as those listed in Chapter 4.

2. Procedure

   2.1 Sample preparation and extraction

   A ten-gram sample from a washed Jerusalem artichoke tuber was

sliced into 1/16" (15mm) pieces and was placed in a 100 mℓ flask. 40 mℓ of distilled water and 2 grams of $CaCO_3$ were added to the flask that was placed in a water bath at 80°C for 1 hour to extract the juice. 2 mℓ of a saturated neutral solution of lead acetate, $Pb(C_2H_3O_2)_2 \cdot 3H_2O$ was added to clarify the extract, and the excess lead was removed by 2ml of a 3% (w/v) sodium carbonate solution.

2.2 Conversion

To study the effects of the pH of extract and reaction time on the yield of reducing sugar, fixed aliquots were taken from the extract and diluted to suitable volumes in flasks. The diluted aliquots were then adjusted to five pH levels, 1.25, 1.50, 1.75, 2.00, and 3.00. Three 1 mℓ samples were taken from each flask. These three samples were then heated at 80°C for 10, 20, 30, 60, 90 or 150 minutes. Reducing sugar contents of the samples (total of 90) was then determined by the Dinitrosalicylic Acid Reagent (DNS) method. To study the effects of the pH of extract and reaction temperature on the yield of reducing sugar, three 1 mℓ samples were taken from each flask containing Jerusalem artichoke extract with a pH of 1.25, 1.50, 1.75, 2.00, or 3.00. These three samples were heated at 50°, 60°, 65°, 70°, 75° or 90°C for one hour.

The reducing sugar contents of the samples (total of 90) was determined made by the DNS method.

To study the effects of reaction time and temperature on the yield of reducing sugar, pH of the sample was fixed at 1.5. Three 1 mℓ samples were taken from the Jerusalem artichoke extract. Each sample was then heated at 50°, 60°, 65°, 70°, 75° or 90°C for 10, 20, 30, 90 or 150 minutes.

Reducing sugar contents of the total of 90 samples was determined by the DNS method.

3. Analytical Method

The DNS method was used to determine the reducing sugar contents in the hydrolyzed Jerusalem artichoke extract. The preparation of the reagent and the procedure used have been described in detail in Chapter 4.

RESULTS AND DISCUSSION

The results obtained in this investigation are presented mainly in graphical form. They are analyzed and discussed in the following sections.

Effects of the Reaction Time and pH of Extract on the Yield of Reducing Sugar

Figure 1 shows the effects of pH and the reaction time at a hydrolysis temperature of 80°C on the yield of reducing sugar. Combinations of pH and reaction time, corresponding to the maximum yields of between approximately 95% and 100%, in terms of grams of reducing sugar per 100 grams of fresh Jerusalem artichoke tubers, are given below as examples:

pH = 1.25 and time = 20 min.; pH = 1.50 and time = 20 min.; pH = 1.75 and time = 60 min.; and pH = 2.00 and time = 150 min.

When the pH was greater than 2.00, yield of reducing sugar was always less than 95% of the maximum yield which, was reached at a pH of 1.5, a reaction temperature of 80°C and a reaction time of one hour. On the other hand, a pH value less than 1.50 did not increase the yield.

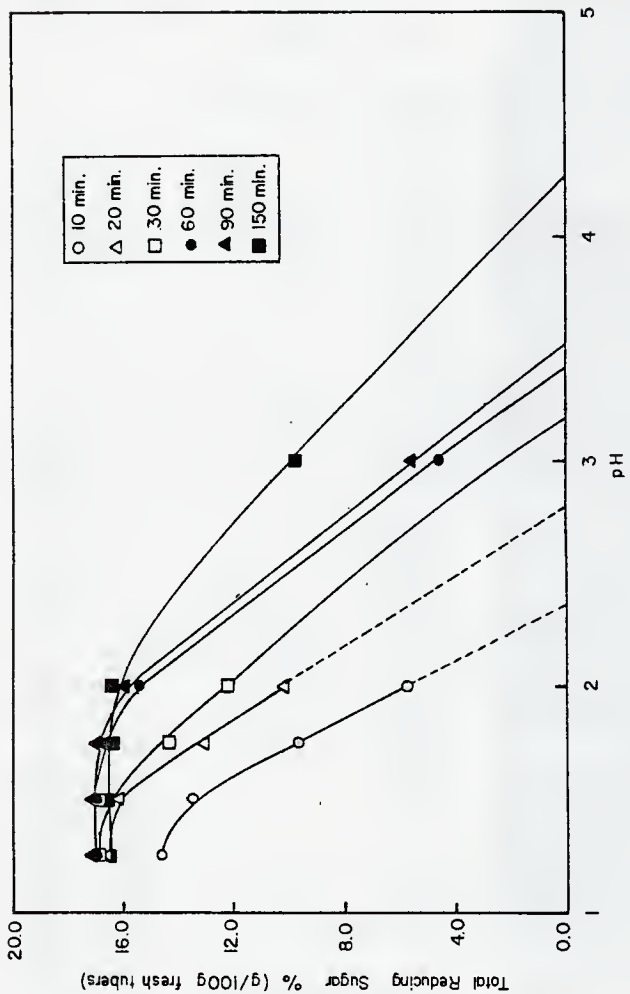


Fig. 1. Effects of Reaction Time and pH of the Extract on the Yield of Total Reducing Sugar at 80°C.

Effects of pH of the Extract and Reaction Temperature on the Yield of Reducing Sugar

Figure 2 illustrates the effects of temperature and pH the extract for hydrolysis time of one hour on the yield of reducing sugar. It clearly shows that the yield of reducing sugar increased with an increase in the temperature for pH between 1.25 and 2.00. However, no further increase in the yield was achieved beyond 80°C; in fact, it resulted in a slight drop on the yield of reducing sugar.

Effects of the Reaction Temperature and Reaction Time on the Yield of Reducing Sugar

Figure 3 shows the effects of reaction time and temperature on the yield of reducing sugar at a pH of 1.5. Up to a temperature of 75°C, the yield was found to increase with the reaction time. At reaction temperatures of 80°C and 90°C, the yield increased up to the reaction times of 90 minutes and 60 minutes, respectively, and thereafter, the yield decreased. This decrease can be attributed to the decomposition of reducing sugar (fructose) (Eichinger et al., 1932). At 80°C, the maximum yield of 97.9% was reached in 30 minutes. Based on these results, the optimal condition for conversion of polysaccharides (inulin) to reducing sugar corresponds approximately to the reaction temperature of 80°C, the reaction time of 30 minutes, and a pH of 1.5.

Hydrolysis Kinetics of Inulin to Fructose Reaction

According to McDonald (1969), the hydrolysis reaction of inulin to fructose can be written as

$$\underset{\text{Inulin}}{(C_6H_{10}O_5)_m \cdot H_2O} + H_2O \xrightarrow{H^+} \underset{\text{Fructose}}{mC_6H_{12}O_6} \qquad (1)$$

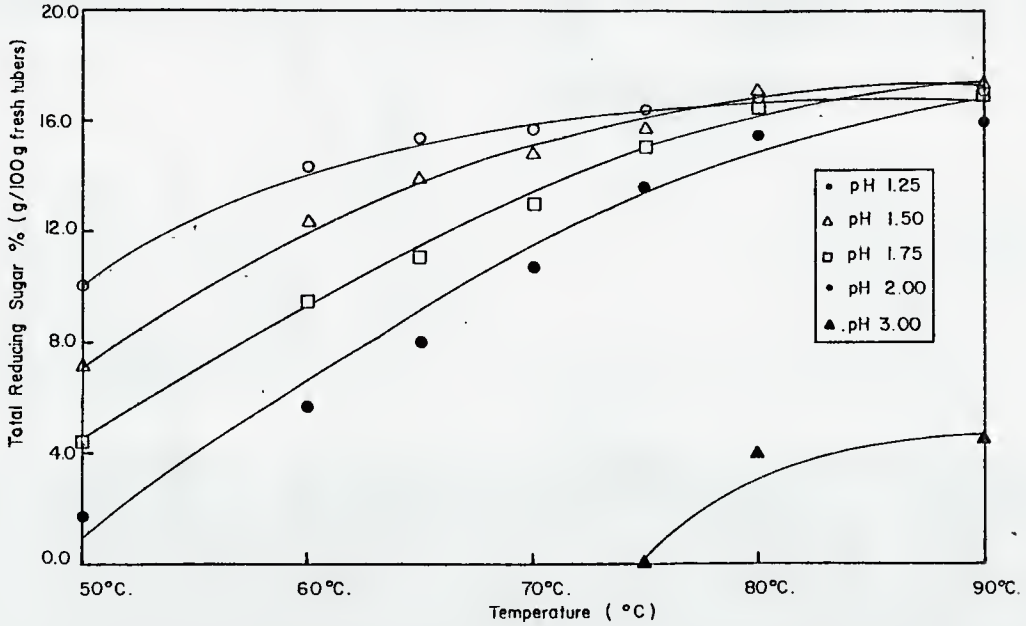


Fig. 2. Effects of pH of the Extract and the Reaction Temperature on the Yield of Total Reducing Sugar for one hour.

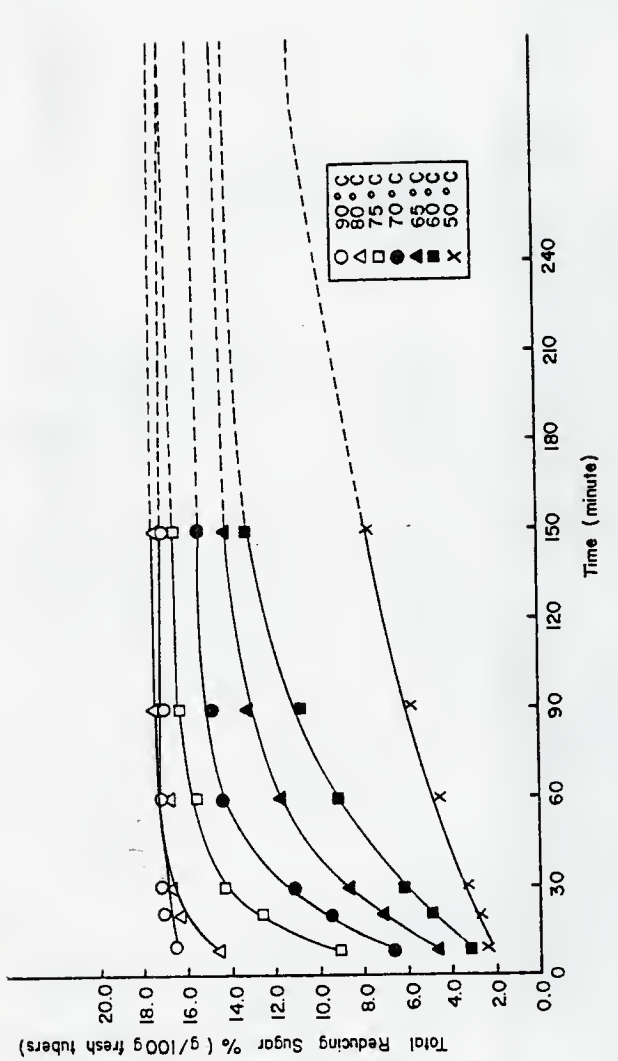


Fig. 3. Effects of the Reaction Temperature and Reaction Time on the Yield of total Reducing Sugar at pH of 1.5.

Because most of the hydrolysis reactions are of the first order, the reaction of inulin to fructose was assumed to be a first order reaction (see, e.g., Pannetier et al., 1967; Webb, 1964; Adamson, 1973). Thus, its rate expression can be written as

$$\frac{dC_p}{dt} = - k C_p \tag{2}$$

where C_p is the concentration of polysaccharide (inulin), t is the time required for the reaction, and k is the rate constant. Since

$$C_p = \frac{1}{m} (C_{r\infty} - C_r), \tag{3}$$

the rate expression can also be written as

$$\frac{d}{dt} [\frac{1}{m} (C_{r\infty} - C_r)] = - k [\frac{1}{m} (C_{r\infty} - C_r)] \tag{4}$$

where C_r is the concentration of fructose (reducing sugar) at any time, $C_{r\infty}$ the concentration of fructose (reducing sugar) at time of infinity (or the maximum concentration of fructose obtainable), and m the number of fructose molecules equivalent to one molecule of inulin.

Equation (4) can be rewritten as

$$\frac{1}{m} \frac{d}{dt} (C_{r\infty} - C_r) = - \frac{k}{m} (C_{r\infty} - C_r)$$

or

$$\frac{d}{dt} (C_{r\infty} - C_r) = - k (C_{r\infty} - C_r) \tag{5}$$

Since $C_{r\infty}$ is a constant, this equation becomes

$$\frac{dC_r}{dt} = k (C_{r\infty} - C_r) \tag{6}$$

Integration gives

$$\int_{C_{r0}}^{C_r} \frac{dC_r}{(C_{r\infty} - C_r)} = \int_0^t k \, dt \tag{7}$$

where C_{r0} is the initial concentration of fructose (reducing sugar). Equation (7) leads to

$$\ell n(C_{r\infty} - C_r) \Big|_{C_{r0}}^{C_r} = kt$$

$$\ell n(C_{r\infty} - C_r) - \ell n\,(C_{r\infty} - C_{r0}) = kt$$

$$\ell n\left(\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}}\right) = kt \qquad (8)$$

where k is the rate constant and is a function of temperature.

To minimize the initial disturbance during the start-up and to establish the desired operating condition, the first sample was obtained at 10 minutes after initiation of heating of the test tubes containing the Jerusalem artichoke extract. The data obtained at five temperature levels of 50°, 60°, 65°, 70° and 75°C are given in Tables 1 through 5. The concentrations were converted into the fractions of inulin unconverted,

$$\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}},$$

the values of which are also given in the same tables. Semi-logarithmic plots of these values as functions of time are shown in Fig. 4, the slopes of which are the values of k. These values of k, which are similar to the values of rate constants obtained by Dykin et al., (1933), are summarized in Table 6. The standard errors of these least square lines ranging from 0.027 to 0.243.

According to the Arrhenius equation (Benson, 1976), the dependency of k on T can be written as

$$k = k_0 e^{-\frac{E}{RT}} \qquad (9)$$

Table 1. Experimental Conversion Data of Inulin to Fructose at 50°C

Time (min.)	C_r (%)	C_r (M)	$C_{r\infty} - C_r$ (M)	$\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}}$	$\ln(\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}})$
0	2.40	0.0133	0.0506	1.0000	-0.0000
10	2.75	0.0153	0.0486	0.9605	-0.0403
20	3.20	0.0178	0.0461	0.9111	-0.0931
50	4.45	0.0247	0.0392	0.7747	-0.2553
80	5.77	0.0321	0.0318	0.6285	-0.4644
140	7.89	0.0438	0.0201	0.3972	-0.9232
∞	11.50	0.0639	0.0000	0.0000	$-\infty$

Note:

1. C_r = Concentration of reducing sugar at any time.
2. $C_{r\infty}$ = Concentration of reducing sugar at time of infinity.
3. C_{r0} = Concentration of reducing sugar at time of zero.
4. M = Molarity

Table 2. Experimental Conversion Data of Inulin to Fructose at 60°C

Time (min.)	C_r (%)	C_r (M)	$C_{r\infty} - C_r$ (M)	$\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}}$	$\ln(\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}})$
0	3.28	0.0182	0.0640	1.0000	0.0000
10	4.77	0.0265	0.0557	0.8705	-0.1387
20	6.10	0.0339	0.0483	0.7551	-0.2809
50	9.03	0.0502	0.0320	0.5008	-0.6916
80	10.85	0.0603	0.0219	0.3432	-1.0694
140	13.02	0.0723	0.0099	0.1560	-1.8579
∞	14.80	0.0822	0.0000	0.0000	- ∞

Note:

1. C_r = concentration of reducing sugar at any time.
2. $C_{r\infty}$ = concentration of reducing sugar at time of infinity.
3. C_{r0} = concentration of reducing sugar at time of zero.
4. M = Molarity

Table 3. Experimental Conversion Data of Inulin to Fructose at 65°C

Time (min.)	C_r		$C_{r\infty} - C_r$	$\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}}$	$\ln\left(\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}}\right)$
	(%)	(M)	(M)		
0	4.77	0.0265	0.0599	1.0000	0.0000
10	6.93	0.0385	0.0479	0.7998	-0.2234
20	8.60	0.0478	0.0386	0.6450	-0.4384
50	11.88	0.0660	0.0204	0.3411	-1.0757
80	13.17	0.0732	0.0132	0.2215	-1.5073
140	14.63	0.0813	0.0051	0.0862	-2.4512
∞	15.56	0.0864	0.0000	0.0000	- ∞

Note:

1. C_r = concentration of reducing sugar at any time.
2. $C_{r\infty}$ = concentration of reducing sugar at time of infinity.
3. C_{r0} = concentration of reducing sugar at time of zero.
4. M = Molarity

Table 4. Experimental Conversion Data of Inulin to Fructose at 70°C

Time (min.)	C_r		$C_{r\infty} - C_r$	$\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}}$	$\ln(\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}})$
	(%)	(M)	(M)		
0	6.67	0.0371	0.0523	1.0000	0.0000
10	9.54	0.0530	0.0364	0.6957	-0.3629
20	11.71	0.0651	0.0243	0.4655	-0.7646
50	14.20	0.0789	0.0105	0.2015	-1.6020
80	14.80	0.0822	0.0072	0.1379	-1.9815
140	15.60	0.0867	0.0027	0.0530	-2.9370
∞	16.10	0.0894	0.0000	0.0000	$-\infty$

Note:

1. C_r = concentration of reducing sugar at any time.
2. $C_{r\infty}$ = concentration of reducing sugar at time of infinity.
3. C_{r0} = concentration of reducing sugar at time of zero.
4. M = Molarity

Table 5. Experimental Conversion Data of Inulin to Fructose at 75°C

Time (min.)	C_r		$C_{r\infty} - C_r$	$\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}}$	$\ln(\frac{C_{r\infty} - C_r}{C_{r\infty} - C_{r0}})$
	(%)	(M)	(M)		
0	9.81	0.0510	0.0412	1.0000	0.0000
10	12.64	0.0702	0.0220	0.5337	-0.6280
20	14.20	0.0789	0.0133	0.3235	-1.1287
50	15.77	0.0876	0.0046	0.1119	-2.1905
80	16.20	0.0900	0.0022	0.0539	-2.9205
140	16.53	0.0918	0.0004	0.0094	-4.6634
∞	16.60	0.0922	0.0000	0.0000	$-\infty$

Note:

1. C_r = concentration of reducing sugar at any time.
2. $C_{r\infty}$ = concentration of reducing sugar at time of infinity.
3. C_{r0} = concentration of reducing sugar at time of zero.
4. M = Molarity

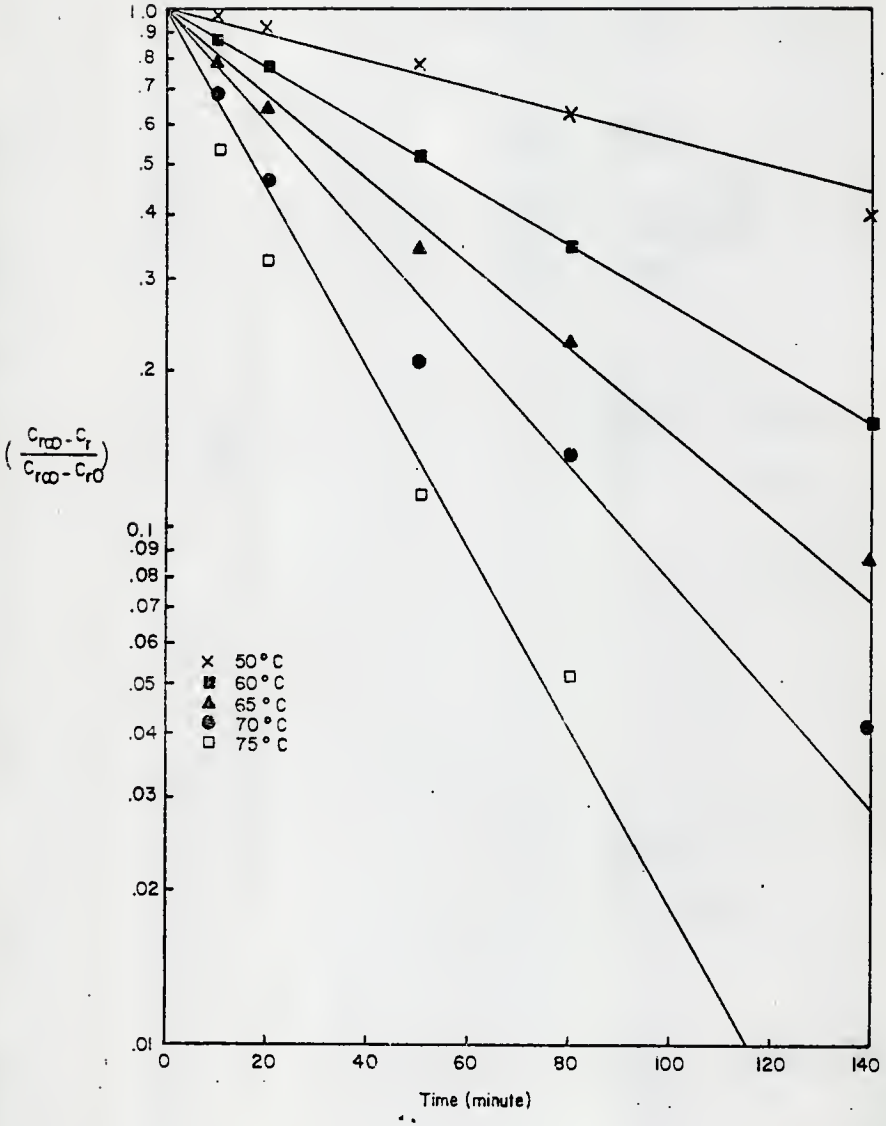


Fig. 4. Fractional Unconverted Inulin Concentration vs. Time.

where k_0 is the frequency factor, E the activation energy (calories/g-mole), R the gas constant (= 1.987 cal./g-mole °K), and T the absolute temperature (°Kelvin). Equation (9) can be rewritten as

$$\ln k = \ln\left(k_0 e^{-\frac{E}{RT}}\right)$$

$$= \ln k_0 - \left(\frac{E}{R}\right)\frac{1}{T}$$

A semi-logarithmic plot of k as a function of $\frac{1}{T}$ is shown in Fig. 5, the slope of which is $(-\frac{E}{R})$ and the standard error of this least square line is 0.3345. The activation energy E was recovered from it as 13,442.1 calories/g-mole. This value is within the range of the activation energies of hydrolysis reactions in homogeneous solutions (Bray et al., 1966; Laidler, 1966; Netter, 1969). This value is essentially in agreement with the approximate activation energy value of 15098.7 calories/g-mole which is recovered here from the data of Dykins et al. (1933) under a condition of a mean pH of approximately 3.5. Similar results were obtained by another method of data analysis (see Appendix 1).

CONCLUSION

In general, the yield of reducing sugar (mainly fructose) from the conversion of polysaccharides (mainly inulin) in Jerusalem artichoke extract increased as the pH of the extract was decreased and the reaction time was prolonged to a certain level. However, the detrimental effect of high acidity and high temperature caused the destruction of fructose. The experimental results show that the yield of reducing sugar increased markedly when pH was increased from 1.50 to 2.00, and the reaction temperature was increased up to 80°C for the reaction time of up to 60 minutes.

Table 6. The Hydrolysis $(C_6H_{10}O_5)_m \cdot H_2O + H_2O \rightarrow mC_6H_{12}O_6$

Temperature (°K)	1/T* ($°K^{-1}$)	k** ($min.^{-1}$)	ℓn k
323	3.096×10^{-3}	0.0066	-5.0207
333	3.003×10^{-3}	0.0132	-4.3275
338	2.959×10^{-3}	0.0174	-4.0513
343	2.915×10^{-3}	0.0205	-3.8873
348	2.873×10^{-3}	0.0320	-3.4420

* T is the absolute temperature

** k is the rate constant at a given temperature

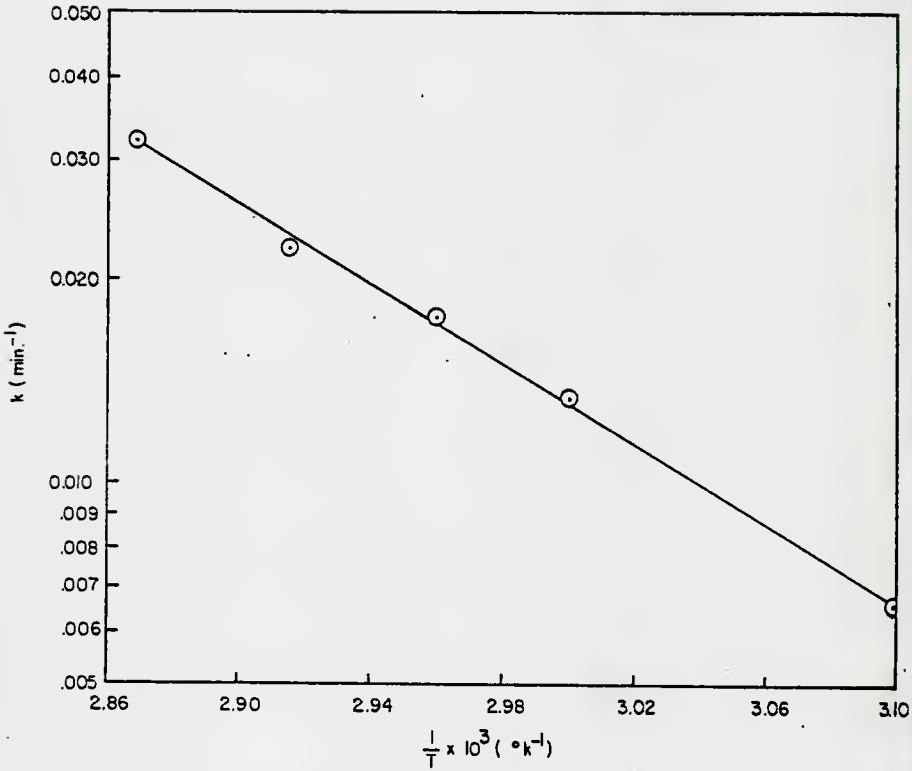


Fig. 5. Arrhenins plot for the Hydrolysis $(C_6H_{10}O_5)_m \cdot H_2O + H_2O \longrightarrow mC_6H_{12}O_6$.

The most favorable conditions for the conversion of inulin from Jerusalem artichoke extract to fructose was found at a pH of 1.5, a temperature of 80°C and a reaction time of 30 minutes. The hydrolysis reaction of inulin to fructose was found to be a first-order reaction and an activation energy of 13442.1 calories/g-mole was obtained.

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CHAPTER 6

ALCOHOLIC FERMENTATION OF JERUSALEM ARTICHOKE TUBERS

INTRODUCTION

Low-cost, plentiful and dependable supplies of energy have contributed to the economic growth and prosperity (Miller, 1973); however, such supplies of energy are rapidly running out. Even though there are many potential substitutes for energy sources, some of them cannot be utilized ecomomically with the present state of technological development. Tidal and nuclear energy represent two such sources (Calvin, 1977).

Biomass is now the major source of renewable energy. Plants convert solar energy into usable and storable forms of energy. For example, the industrial use of agricultural crops through fermentation of sugars by yeast into alcohol is well known (Prescott, 1940; Miller, 1974).

It should be emphasized that the suitability of any particular raw material or crop for a large-scale production of alcohol is primarily dependent upon the cost of producing unit volume (e.g. one gallon) or mass of alcohol from the material. This cost is largely governed by three factors (Monier-Williams, 1922):

(a) Content of fermentable carbohydrates in the material

(b) Yield of crop per unit area, e.g., acre

(c) Availability of the material, i.e., the relative labor involved in cultivation and the ease and certainty with which a constant annual supply can be maintained.

As stated earlier, Jerusalem artichoke tubers contain about 17% fermentable carbohydrate. The average yield of the Jerusalem artichoke

tubers ranges from 10 to 15 tons per acre, and some estimates are as high as 30 tons per acre; this high yield can compensate for the low percentage of fermentable carbohydrate (Prescott, 1940). It is also very easy to cultivate, because it is strongly resistant to frost, diseases and insects (Sebert, 1974).

Although they contain high contents of starch, in some cereal grains, such as wheat and corn, give a low yield per acre and are not always available as raw materials for alcohol, because they are too valuable as food stuffs and are too expensive. Some root crops, e.g., beets, which are comparatively poor in sugar contents, give high yield per acre. Their cultivation, however, makes heavier demands upon labor than cereal grains.

What has been discussed indicates that the liquid fuel - alcohol from Jerusalem artichoke, which is described as indigenous "weed", is a substitute energy with high potential. The objective of this work was to determine the technical feasibility of alcoholic fermentation from Jerusalem artichoke tubers by several different approaches.

The first phase of this work was carried out in two series. In one series, alcoholic fermentation of unclarified-unhydrolyzed Jerusalem artichoke juice, clarified-unhydrolyzed Jerusalem artichoke juice and clarified-hydrolyzed Jerusalem artichoke juice was carried out in flasks placed in an incubator-shaker. The contents of the flasks were sampled at regular time intervals. In other series, alcoholic fermentation was carried out without interval sampling.

In the second phase of this work, clarified-hydrolyzed Jerusalem artichoke juice was used as raw material and alcoholic fermentation was

carried out in a fermentor under an absolute anaerobic condition. The contents of the fermentor were sampled at regular time intervals.

FUNDAMENTALS OF ALCOHOLIC FERMENTATION

Alcoholic fermentation converts hexose sugars into alcohol and carbon dioxide accompanied by the liberation of energy in the form of heat. Alcoholic fermentation is an anaerobic process carried on by living yeast cells (Lee, 1975).

Jerusalem artichoke tubers are rich in the polysaccharide, inulin, $(C_6H_{10}O_5)_n$, which is a fructose polymer and is readily hydrolyzed to fructose (Barker, 1976). The overall chemical reaction of the conversion process of inulin to alcohol is shown below (Miller, 1973; Calvin, 1977),

$$(C_6H_{10}O)_n + nH_2O \longrightarrow nC_6H_{12}O_6$$

inulin → fructose

$$C_6H_{12}O_6 \longrightarrow 2\ C_2H_5OH + 2\ CO_2$$

fructose	alcohol	carbon dioxide
180 g	92 g	
(673 kcal)	(655 kcal)	

If 100% of fructose is utilized, 92 gm of alcohol would be obtained from 180 gm of fructose (hexose), and energy loss is negligibly small (Calvin, 1976). The theoretical yield of alcohol is 0.568 units per unit of inulin or 0.511 units per one unit of fructose. This theoretical yield can never be attained because a part of the sugar is used

by the yeast cells for growth, and a part is converted into small quantites of other carbon compounds. The practical yield ranges between 90 to 95% of the theoretical yield (Lee, 1975).

EXPERIMENTAL

The Jerusalem artichoke tubers for the alcoholic fermentation were obtained from a local grocery store. These tubers were grown in California and packed by Produce Specialties, Inc., in one-pound bags, each holding only 1 to 2 tubers which looked like potatoes but bigger. The appearance of the tubers was not knobby but regular. The composition of the tubers based on the wet basis was as follows: dry matter, 20.83%; carbohydrate, 18.79%; protein, 1.08%; fat, 0.12%; crude fiber, 0.51%; ash, 0.94%.

Materials, equipment, apparatus, and procedures employed are described below.

1. Materials

The feeds in the first phase of this work and their preparation are given below:

(a) Unclarified-unhydrolyzed Jerusalem artichoke juice. 100 grams of thinly sliced tubers were placed in each 500 ml baffled-bottom Erlenmyer flask. Water was added to the flask to 250 ml, and the mixture was cooked at 80°C for 60 minutes in a water bath. Juice was obtained by extracting and pressing this mixture.

(b) Clarified-unhydrolyzed Jerusalem artichoke juice. The sample preparation method was the same as that employed in preparing unclarified-unhydrolyzed Jerusalem artichoke juice except that the juice was filtered after cooking and was clarified with lead acetate which was removed by sodium carbonate. The filtrates were centrifuged to obtain a clear solution.

(c) Clarified-hydrolyzed Jerusalem artichoke juice. The

preparation method was the same as that used in preparing clarified-unhydrolyzed Jerusalem artichoke juice but this unhydrolyzed juice was further acidified by adding hydrolchloric acid to a pH of 1.5, and the solution was held in a water bath at 80°C for one hour. The carbohydrate equivalent of 9.68 grams of reducing sugars was obtained from 100 grams of fresh tubers.

The raw material prepared for the second phase of alcoholic fermentation is as follows.

The feed was clarified-hydrolyzed Jerusalem artichoke juice which has been prepared in the same manner as that employed in the first phase. The juice was diluted to the carbohydrate equivalent of 8.48 grams of reducing sugars per 100 grams of fresh tubers.

2. Equipment and Apparatus

Both series of alcoholic fermentation in the first phase were carried out in 500 ml baffled-bottom Erlenmyer flasks and placed in a New Brunswick Scientific incubator-shaker,, Model G26. This is a controlled environment incubator-shaker, integrated with a continuous-duty shaking mechanism designed to acheive a wide range of shaking speeds and temperature. In the second phase, alcoholic fermentation of clarified-hydrolyzed Jerusalem artichoke juice was conducted in a New Brunswick Scientific fermentor, Model 19, shown in Fig. 1. This is a bench-scale fermentor, equipped with a self-supporting fermentor glass vessel with a metal top plate. Each unit has a control panel that permits the regulation of agitation, acidity and temperature. It is also equipped with a mechanical foam breaker.

3. Procedure

3.1 Initial preparation



Fig. 1. Fermentor for Alcoholic Fermentation and Methane Gas Digestion of Jerusalem Artichoke.

All the feed for the experiments in the first phase were adjusted with NaOH and HCl to pH 5.5. The culture medium, containing 2.5g/liter of peptone, 1.0 g/liter of KH_2PO_4 and 3.0 g/liter of $MgSO_4 \cdot 7H_2O$, was added to each flask, and all of the flasks were sterilized in an autoclave at a pressure of 15 psig for 20 minutes. After sterilization, flasks were sealed with aluminum foil.

For the experiments in the second phase, 3500 ml of the diluted juice were adjusted to pH 5.5, and the culture medium for yeast growth, containing 2.5g/liter of peptone, 1.0 g/liter of KH_2PO_4 and 3.0 g/liter of $MgSO_4 \cdot 7H_2O$, was added to a clean fermentor jar. It was covered with a metal top plate and was sterilized in an autoclave at a pressure of 15 psig for 40 minutes. The fermentor jar was subsequently fitted into the main fermentor unit.

3.2 Inoculum buildup (Seed Culture Preparation)

Stock cultures of yeast (ATCC No. 22574) were maintained on YM (yeast medium) agar slants at 4°C. The composition of this agar is shown in Table 1. An inoculum was prepared by aseptically transferring fungal colonies from the stock cultures to a fresh agar slant and incubating at 30°C. At the end of 48 hours, several loops of fungal growth from the agar slants were aseptically transferred to a liquid inoculation medium, and its composition appears in Table 2. The fungal inoculum was cultured for 48 hours in an environmentally controlled incubator-shaker at an agitation speed of 250 rpm and a temperature of 30°C.

3.3 Fermentation

Approximately 10% (vol/vol) of seed culture (yeast ATCC 22574)

TABLE 1. Composition of Yeast Medium Agar (YM Agar)*

Yeast Extract	3g
Malt Extract	3g
Peptone	5g
Dextrose	10g
Agar	20g

*Weights of each ingredient per liter of solution

TABLE 2. Composition of Liquid Inoculation Medium for Yeast*

Sucrose	100.0g
Peptone	2.5g
KH_2PO_4	1.0g
$MgSO_4$	3.0g

*Weights of each ingredients per liter of solution

was used to inoculate the Jerusalem artichoke medium in each Erlenmeyer flask. Fungal growth was carried out in an incubator-shaker at a agitation speed of 250 rpm and a temperature of 30°C. In one series, a 15 ml sample was taken from each flask at regular time intervals of about 8 hours to assess the progress of the fermentation. Aseptic precautions were taken throughout the sampling procedure. In the other series, no interval samples were taken from the flasks. The fermentation was carried out for about 4 days.

In the second phase, approximately 10% (vol/vol) of seed culture (yeast ATCC 22574) was used to inoculate the Jerusalem artichoke medium in a 14-liter fermentor jar which was fitted into the main fermentor unit, and fermentation was anaerobic. Fungal growth was carried out at an agitation speed of 150 rpm and at a temperature of 30°C. An attempt was made to control pH with ammonium hydroxide. The "precision" wet test meter was connected to the fermentor jar to measure the amount of gas (CO_2) produced. Samples for checking the yield of alcohol were taken at regular time intervals through the sampling tube. A 30 ml sample was collected each time, after discarding approximately a 20 ml aliquot comprising the dead volume in the sampling tube. Aseptic precautions were also taken throughout the sampling procedure.

4. Analytical Method

The carbohydrate content of the materials employed was determined before and after fermentation by estimating the reducing sugars (fructose and glucose) by the dinitrosalicylic acid (DNS) method which was described previously.

The alcohol content of the fermented product was analyzed by distilling a measured volume of the product with a simple distillation apparatus which is also shown in Fig. 1. Collecting the distillate in round-bottom distilling flasks and determining the specific gravity of the distillate with a "Mettler H51" analytical balance, the alcohol concentration was then read from appropriate tables. The amount of gas (CO_2) produced from the fermented medium was recorded at each sampling time, and the pH of the medium in the fermentor jar was also recorded.

RESULTS AND DISCUSSION

The experimental results presented in Tables 3 and 4 and also plotted in Fig. 2 are generally expressed in terms of the weight of alcohol per 100 grams of fresh Jerusalem artichoke tubers and in percent of the theoretical conversion of the total carbohydrate to alcohol according to the equation:

$$C_6H_{12}O_6 \longrightarrow 2CO_2 + 2C_2H_5OH$$

1. First Phase

Each experiment of the first phase lasted about three days. The results are given in Table 3. This table shows that the yield of alcohol was relatively low in the first series where samples were withdrawn at regular time intervals. The actual yields from the three feed materials were found to be 42.98%, 34.43% and 32.79% of the theoretical yield obtainable from unclarified-unhydrolyzed Jerusalem artichoke juice. It was concluded that the anaerobic condition necessary for yeast growth was not obtained. The yields of alcohol were highly improved in the second series which will be discussed later.

TABLE 3. Alcoholic Fermentation of Jerusalem Artichoke Tubers in Incubaor Shaker

Raw Material	Total R.S.*	EtOH yield with sample taken		EtOH yield without sample taken	
	g/100g fresh tuber	g/100g fresh tuber	% of theoretical yield	g/100g fresh tuber	% of theoretical yield
Unclarified-unhydrolyzed Jerusalem artichoke juice	9.68	2.126	42.98	4.479	90.55
Clarified-unhydrolyzed Jerusalem artichoke juice	9.68	1.703	34.43	3.967	80.20
Clarified-hydrolyzed Jerusalem artichoke juice	9.68	1.622	32.79	3.947	79.80

*Total reducing sugar.

The fermentation was completed within about 33 hours for unclarified-unhydrolyzed Jerusalem artichoke juice, about 48 hours for clarified-unhydrolyzed Jerusalem artichoke juice, and about 56 hours for clarified-hydrolyzed Jerusalem artichoke juice.

The yields of alcohol from the second series of experiments, from which without samples were not withdrawn at regular time intervals were better than those from the first series. They were 90.55%, 80.20%, 79.80% of the theoretical value for unclarified-unhydrolyzed Jerusalem artichoke juice, clarified-unhydrolyzed Jerusalem artichoke juice, and clarified-hydrolyzed Jerusalem artichoke juice, respectively. The fact that the yield of alcohol from unclarified-unhydrolyzed Jerusalem artichoke juice was highest was probably due to this juice was only extracted in water and no chemicals which are detrimental to yeast, e.g., lead acetate, were used during the juice preparation step.

2. Second Phase

The second phase of the experiment, in which clarified-hydrolyzed Jerusalem artichoke juice was fermented, lasted for about four days. The results are given in Table 4 and are also plotted in Fig. 2.

The actual yield of alcohol obtained in this phase was 87.5% of the theoretical value. In this phase, every attempt was made to maintain an absolute anaerobic condition. The percentage of reducing sugar decreased as the alcohol and carbon dioxide increased; approximately 75 hours were required to reach the maximum yield of alcohol, as shown in Fig. 2.

The reason for utilizing clarified-hydrolyzed Jerusalem artichoke juice in this phase was to examine the relationship between the contents

TABLE 4. Results of Alcoholic Fermentation of Jerusalem Artichoke Tubers in Fermentor

Time	Reducing Sugar	Alcohol yield		CO_2	
	g/100g fresh tuber	g/100g fresh tuber	% of theory	*ft^3	**g/100g fresh tuber
0:00	8.48	0.00	0.0	0.0000	0.00
6:00	7.51	0.13	3.0	0.0000	0.00
12:30	7.02	0.37	9.0	0.0000	0.00
17:00	6.53	0.50	12.0	0.0650	0.13
22:00	5.48	0.65	15.0	0.3049	0.62
27:00	4.30	1.38	31.8	0.5845	1.19
31:40	3.45	1.81	41.8	0.8525	1.74
40:40	2.08	2.18	50.3	1.1188	2.28
45:40	1.76	2.31	53.3	1.3122	2.67
51:00	1.48	2.59	59.8	1.3771	2.81
54:30	1.18	2.81	64.8	1.4106	2.88
63:30	0.00	3.59	82.8	1.4926	3.04
69:00	0.00	3.79	87.5	1.5138	3.09
76:00	0.00	3.78	87.2	1.5143	3.09
93:00	0.00	3.78	87.2	1.5156	3.09

* based on 2500 gms of total weight of Jerusalem artichoke
** based on 100 gms fresh tuber, $PV = nRT$, $W = n \times$ (M.W. of CO_2)
$P = 1$ atm, $R = 0.08205$ liter-atm $(°K)^{-1}$, $T = 298°K$.

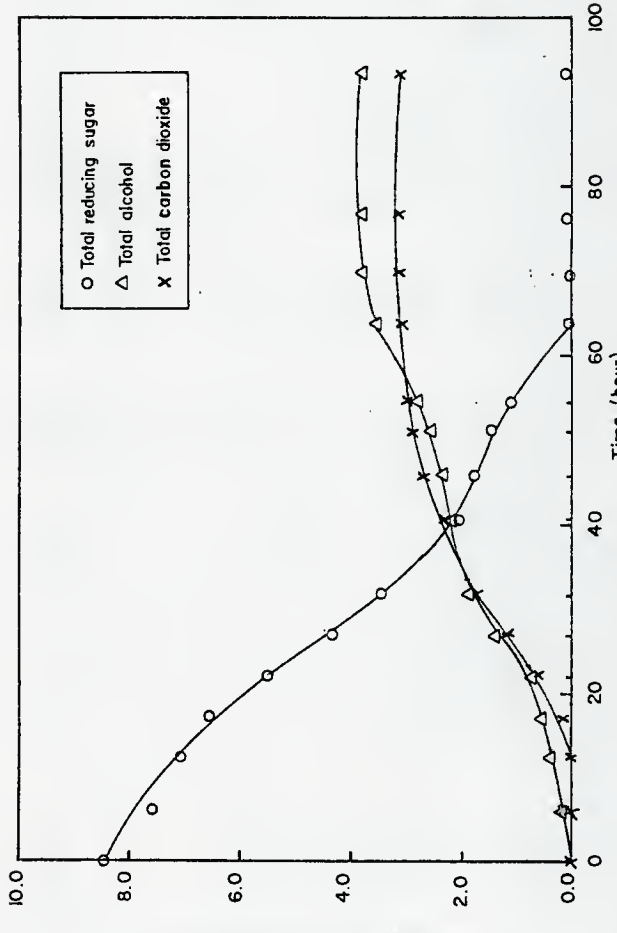


Fig. 2. Cumulative Sugar Consumption in Alcoholic Fermentation of Jerusalem Artichoke Tubers in Fermentor.

of reducing sugar that decrease and the content of alcohol that increase. The relationship could not be examined if an unhydrolyzed Jerusalem artichoke juice was used, because the yeast ferments the polysaccharide (inulin) of Jerusalem artichoke tubers into alcohol inside its cells and thus the reducing sugar can not exist in the juice.

Results from the first phase appear to indicate two points. First, it is not necessary to clarify the juice of Jerusalem artichoke before alcoholic fermentation. Second, since the complete hydrolysis did not improve the yield of alcohol, it is not necessary to hydrolyze the juice prior to fermentation. These are also in agreement with the findings of Underkofler (1937).

The actual yield of 87.5% of the theoretical value obtained in the second phase should be considered fairly good, even though it was slightly lower than the maximum yield of 90.55% obtained in the first phase.

CONCLUSION

The results of this work show conclusively that the Jerusalem artichoke possesses a high potential as a raw material for the production of alcohol. The yield, the rate of production of alcohol produced from the juice of Jerusalem artichoke tubers depend on many factors, some of which are agitation speed, fermentation condition (aerobic or anaerobic), type of equipment (flask or fermentor), mode of preparation of the fermentation medium. Obviously, alcoholic fermentation should be carried out anaerobically, and it is more desirable to carry out

fermentation in a fermentor than in a flask. To obtain a high yield of alcohol, it is not necessary to clarify and hydrolyze the juice of Jerusalem artichoke tubers. Eliminating these steps also reduces the cost of alcohol production.

The results from both phases indicate that yeast can utilize the inulin in Jerusalem artichoke tubers without hydrolyzing it into simple sugars and that if the Jerusalem artichoke medium (juice) is added to the medium of seed culture for yeast adaptation, the alcohol production probably can further be increased. It is also well known that there are several other methods, such as the batch fed method and vacuum fermentation, available to increase the yield of alcohol fermentation.

Besides the juice from tubers, leaves and stalks of Jerusalem Artichoke and even cellulosic wastes from tuber processing can be converted into alcohol by various means. This means including enzymatic or acidic hydrolysis followed by fermentation.

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CHAPTER 7

METHANE GAS PRODUCTION FROM JERUSALEM ARTICHOKE TUBERS

INTRODUCTION

The continuing pressure for a clean burning fuel has created such a demand for natural gas that the gas reserves in this country are being severely depleted. It has been predicted that this demand will greatly exceed the supply in the future (see, e.g., Bell et al., 1972; Pfeffer, 1973; Calvin, 1976). The production of a substitute fuel gas is a viable way of extending the life of well-developed technology for converting gas into useful forms of energy.

Among the gaseous fuel substitutes, methane from the conversion of biomass is well known. Extensive research has been carried out in this area, including such processes as anaerobic digestion and pyrolysis of livestock manure, crop waste, and sewage sludges (see, e.g., Walawender et al., 1972; Converse et al., 1975; Engler et al., 1975; Clausen et al., 1976; Clark et al., 1977), and most of the processes have been proved technically feasible. The effort is now oriented toward studies of the economic feasibility of constructing a large methane plant (Keenan, 1975; Clausen et al., 1976).

Because the productivity of Jerusalem artichoke tubers is fairly high and also because their use as raw material in the manufacture of sugar would result in a waste of a rather offensive nature, it seems advisable to study the anaerobic digestion of fresh or processed tubers that give rise to production of methane. The objective of this work was to investigate the technical feasibility of methane production from the anaerobic digestion of fresh Jerusalem artichoke tubers by using a single stage digester.

FUNDAMENTALS OF ANAEROBIC DIGESTION

Anaerobic digestion is a biological process in which heterogeneous groups of bacteria, in the absence of molecular oxygen, carry out the stepwise degradation of organic materials, such as fats, proteins and carbohydrates (see, e.g., Keenan, 1975; Compere et al., 1975; Meynell, 1976). A schematic of the process and a qualitative material balance are shown in Fig. 1 (Fry et al., 1973; Keenan, 1975).

In the first stage of digestion, organic material which is digestible is hydrolyzed by acid producing bacteria into simple compounds, such as fatty acids, amino acids, and sugars. The acid producing bacteria can further digest these simple compounds to volatile fatty acids, lower alcohols and aldehydes, carbon dioxide, hydrogen, ammonia, hydrogen sulfide, and some molecular nitrogen (Andrews et al., 1975). The two major volatile acids (intermediates) formed in anaerobic treatment are acetic acid and propionic acid (McCarty, 1964).

In the second stage of digestion, methane producing bacteria convert the volatile acids into methane gas. About 70% of the methane produced during digestion comes from acetic acid. Most of the remaining methane in anaerobic treatment is formed from the reduction of carbon dioxide. The major mechanisms of methane formation are shown below (see, e.g., McCarty, 1964; Pine, 1971; Keenan, 1975).

a. Acetic Acid Cleavage:

$$C^*H_3COOH \longrightarrow C^*H_4 + CO_2$$

b. Carbon Dioxide Reduction:

$$CO_2 + 4H_2 \longrightarrow 2H_2O + CH_4$$

The ratio of methane to carbon dioxide depends upon the nature of the initial substrate, and methane typically comprises 60-70 percent by volume

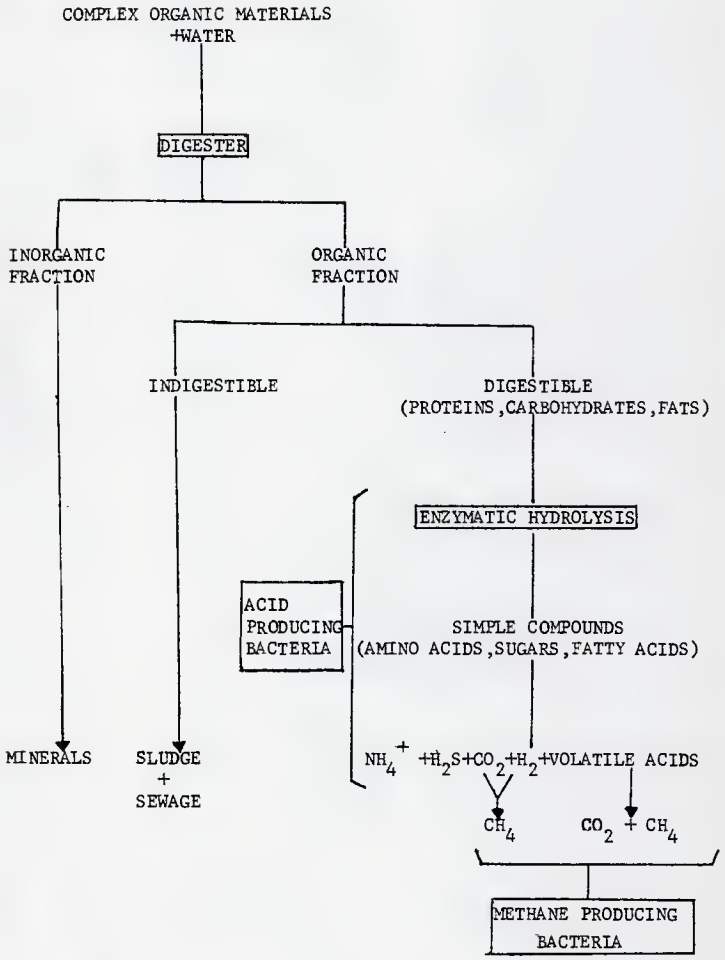


Fig.1. The Biological Breakdown of Biomass in the Anaerobic Digester (Fry et al., 1973; Keenan, 1975).

of the digestion off-gases (Meynell, 1976). The general composition of biogas produced from farm wastes is shown in Table 1 (Fry et al., 1973). Buswell et al. (1952) found the formula which is given below to predict the quantity of methane from a knowledge of the chemical composition of organic wastes.

$$C_nH_aO_b + (n - \frac{a}{4} - \frac{b}{2})\ H_2O \longrightarrow (\frac{n}{2} - \frac{a}{8} + \frac{b}{4})\ CO_2 + (\frac{n}{2} + \frac{a}{8} - \frac{b}{4})\ CH_4$$

Most of organic wastes are made up of a mixture of these three components and the resulting gas composition from their digestion is usually in the range of 60-70% methane and 30-40% carbon dioxide. The anaerobic fermentation, as carried out for the production of methane, differs in many respects from other types of fermentation. The most important difference is perhaps the fact that it is not necessary to use a pure culture of organisms nor is it necessary to maintain "purified" cultures for inoculation or reinoculation (see, e.g., Buswell, 1939; McCarty, 1964). The acid producing bacteria are capable of rapid reproduction and are not very sensitive to changes in their environment. But methane bacteria reproduce slowly and are very sensitive to changes in the conditions of their environment, such as pH and temperature (Meynell, 1976).

EXPERIMENTAL

The Jerusalem artichoke tubers for the anaerobic digestion of methane gas were obtained from Farmer Seed & Nursery Co., Faribault, Minnesota. The size and shape of these tubers was very uniform. They had the appearance of potatoes but their size was slightly smaller than potatoes. Their skin was thicker than those of the other hybrid tubers used in this research and thus had better moisture keeping quality.

Table 1. General Composition of Bio-gas Products from Farm Wastes (Fry et al., 1973)

		*%
CH_4	Methane	54-70
CO_2	Carbon dioxide	27-45
N_2	Nitrogen	.5-3
H_2	Hydrogen	1-10
CO	Carbon monoxide	0.01
O_2	Oxygen	0.1
H_2S	Hydrogen sulfide	trace

*The percent based on volume of the digester off-gases.

Equipment, apparatus and procedure employed in the experiments are described below.

1. Equipment and apparatus

The anaerobic digestion of Jerusalem artichoke tubers was conducted by using a single stage digester, in which both acidogenic and methanogenic bacteria were present in the same batch. A New Brunswick Scientific fermentor, Model 19, was used as the digester. It is shown in Fig. 1 of the preceding chapter. This is a bench-scale fermentor and can provide an environment for the study of anaerobic digestion of biological waste under controlled conditions. It has a cylindrical plexiglass fermentor jar with a metal top lid and provides a maximum volume of 14 liters. The fermentor contains a series of ports for the insertion of the heater element, sensing probes, and various gas and liquid feed lines.

2. Procedure

2.1 Preparation

4.5 liters (total volume) of the feed for the first or original batch contained 3% (vol./vol.) of dry Jerusalem artichoke tubers, 5% (vol./vol.) of seeding sludge, and the culture medium for the growth of methane producing bacteria. Because the density of this batch of feed was nearly equal to that of water, the 3% (135 ml) by volume was approximately equivalent to 3% by weight or 135 grams of dry Jerusalem artichoke tubers. Since the moisture content of the fresh Jerusalem artichoke tuber was 80.29%, 684 grams of finely ground fresh Jerusalem artichoke tubers were required in the first (original) batch.

The seeding sludge was obtained from an anaerobic sewage disposal plant because it had already been digested anaerobically and contained a large number of required bacteria (Meynell, 1976). The composition of the

culture medium for the growth of methane producing bacteria is shown in Table 2 (Bewersdorff et al., 1971).

The second batch was created by adding 684 grams of freshly ground Jerusalem artichoke tubers into the residue of the first (original) batch in which the gas production was completely stopped.

2.2 Digestion

The fermentation vessel was equipped with sensing probes for the measurement and control of pH and temperature. Digestion of Jerusalem artichoke tubers was carried out at an agitation speed of 200 rpm and at a temperature of 35°C under anaerobic condition. The pH of the system was maintained at around 5.5 by a 0.1 N ammonium hydroxide solution. Foaming was controlled by a mechanical foam breaker.

The anaerobic digestion was closely observed for about 177 hours for the original batch, and for approximately 165 additional hours for the second batch.

The course of anaerobic digestion was followed by measurements of gas volume by using a "Presicion" wet test meter which was connected to the tube on the lid of the fermentor jar. The amount of gas and the pH were recorded at regular time intervals and the temperature was recorded continuously on a single strip Beckman Chart.

RESULTS AND DISCUSSION

The results are shown in Fig. 2. In this figure, the second batch was plotted from time zero for comparison with the first or original batch.

The total gas production was 0.8202 cu. ft. for the first or original batch and 0.8030 cu. ft. for the second or additional batch based on a total green weight of 684 grams of Jerusalem artichoke tubers for each

Table 2. The Composition of the Aqueous Liquid Medium for Methane Producing Bacteria (Bewersdorff et al., 1971)*

$Na_2HPO_4 \cdot 2H_2O$	0.6g
KH_2PO_4	0.4g
$MgSo_4 \cdot 7H_2O$	0.2g
NH_4Cl	0.8g
$FeCl_3 \cdot 6H_2O$	8.35mg
$CaCl_2 \cdot 2H_2O$	0.33mg
$ZnSo_4 \cdot 7H_2O$	0.09mg
$CuSO_4 \cdot 5H_2O$	0.08mg
$MnSo_4 \cdot 4H_2O$	0.08mg
$CoCl_2 \cdot 6H_2O$	0.09mg
Yeast Extract	300mg

*Ingredients per liter of solution

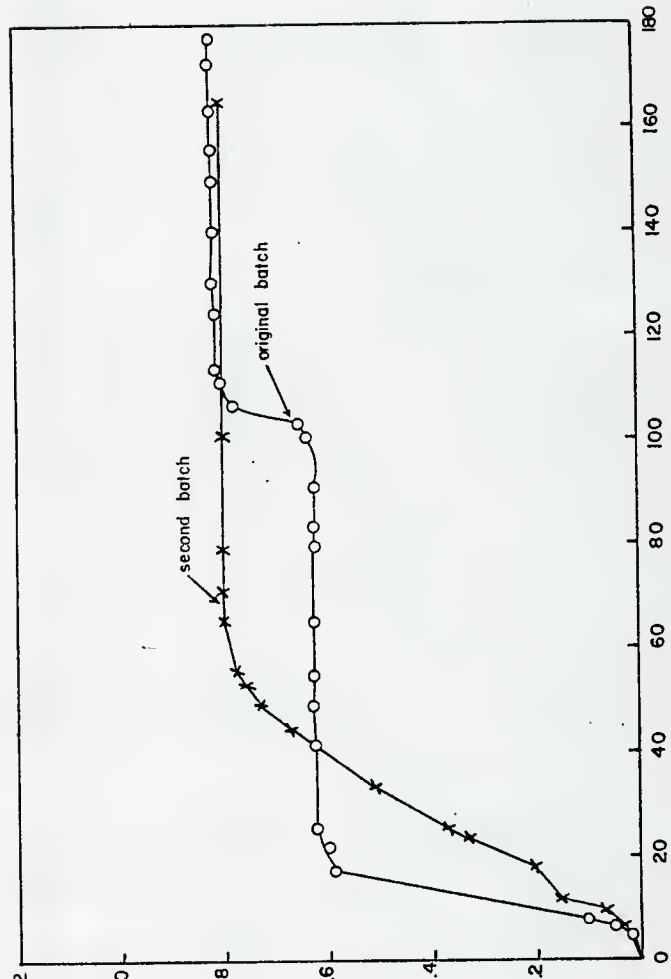


Fig. 2. Anaerobic Digestion of Jerusalem Artichoke Tubers.

batch. This was about $\frac{1}{2}$ ~ $\frac{1}{3}$ of the gas production obtained by Abbott (1933) and Buswell et al. (1939) for Jerusalem artichoke wastes. The reason may have been due to the smaller amount of seeding sludge used in this experiment. In the experiments by Abbott and Buswell et al., the original medium was digested sludge and Jerusalem artichoke wastes were added to it daily. In this work, only 5% of the seeding sludge was used and water was the major portion of the medium; therefore, the gas production can probably be increased by modifying the medium or the procedure according to the experiments of Abbott (1933) and Buswell et al. (1939).

It was easy to distinguish the acid-forming stage and the methane-forming stage in the first or original batch. Approximately three-fourths of the gas was produced in the first 16 hours after the onset of digestion in the acid-forming stage, and the gas production was negligible in the following 84 hours. The methane-forming stage followed and lasted about 14 hours to complete gas production.

Some of the gas produced in the beginning of this batch probably came from the seeding sludge. The reason for the long duration of the acid-forming stage might be that the anaerobic bacteria responsible for digestion could not survive with even the slightest trace of oxygen which was dissolved in the medium. The acid-producing bacteria not only could produce the food for methane-producing bacteria, but they also removed any traces of dissolved oxygen which might remain in the sludge (Fry et al., 1973). Also, the first or original batch probably did not contain sufficient methane-producing bacteria.

Since the methane producing system was already built up in the second batch, it took only about 20 hours to start producing methane gas, and only about 65 hours to complete gas production. Unlike the first batch, the

acid-forming stage and the methane-forming stage of the second batch were not distinct as the first batch, as shown in Fig. 2.

CONCLUSION

The results of this study indicate that about 0.8 cu. ft. of gas can be produced from 135 grams (dry weight) of Jerusalem artichoke tubers. The results also indicate that the batch digestion of Jerusalem artichoke tubers is technically feasible, and the rate of gas production of the second batch after addition of fresh raw material to the residue of the first batch was faster than that of the first (original) batch.

The anaerobic digestion process is considered to be a universal prescription for "free" renewable energy which would save millions in fuel bills since the energy crisis of 1973 (Meynell, 1976). Many improved designs of digesters for methane production have been proposed for increasing the rate and yield of methane gas. The designs include a continuous-flow digester, two-stage digester, and high rate digester (Keenan, 1975). The methane gas production from Jerusalem artichoke tubers will be highly improved with these improved designs.

In addition to methane production, other benefits of the anaerobic digestion of Jerusalem artichoke tubers are also worth mentioning. The benefits include the fact that the sludge obtained from anaerobic digestion can be used as fertilizer or animal feed. Furthermore, other parts of the Jerusalem artichoke, such as stems and leaves, can probably be used as raw material for the production of methane gas after proper pretreatment.

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CHAPTER 8

FOOD VALUE OF JERUSALEM ARTICHOKE

INTRODUCTION

Jeursalem artichoke has been cultivated for centuries as a vegetable by the American Indians who still continue to relish them as a staple winter food. Introduced into Europe by home-coming explorers, this hardy native plant has been grown widely for its succulent tubers and is a familiar vegetable in France and other countries, but Americans are just beginning to learn this easily grown tuber as a table food. An effort was made to improve Jerusalem artichoke during 1940's to obtain new and better strains (Weick, 1943). The tubers of the new strains have a sweeter and more nutty flavor. The improved white-skinned variety requires no peeling.

There are several ways to prepare Jerusalem artichoke tubers which taste and look like potatoes for the table. They can be used in making soups, pies, bread, salads, and even pickles. They should be regarded not as a substitute for potatoes, but as an appetizing vegetable that will do its part to help amateur gardeners solve food shortages (Mayfield, 1974). The tubers of Jerusalem artichoke can be cooked in every way a potato can, except that care must be taken not to over cook or over bake them which makes them soft and soggy. Unless kept moist they lose their crispness in storage, but they can easily be restored by soaking in cold water (Reay, 1968).

One other remarkable quality distinguishes the Jerusalem artichoke: It is a non-starchy vegetable which is recommended not only as food for people with diabetics but also for people who wish to keep down their weight (Larmar, 1955). The reason for adopting Jerusalem artichoke as a diet food is that there is no inulase enzyme in the human digestive tract

to hydrolyze inulin, which is the polysaccharide of the Jerusalem artichoke, to fructose (Salunkne, 1958).

The objective of this work was to conduct a sensory testing to evaluate the acceptibility of Jerusalem artichoke as a food by the facial hedonic method (Ellis, 1966). Jerusalem artichoke chips and mashed Jerusalem artichokes were two samples used in this work.

EXPERIMENTAL

The Jerusalem artichoke for the sample preparation came from the backyard of Dr. L. T. Fan who grew almost all the artichoke tubers for this research. The origin of the seed was Helianthus tuberosus USSR 357304 and was supplied by the North Central Regional Plant, United States Department of Agriculture at Iowa State University. This plant was planted on May 15, 1976 and harvested on October 31, 1976. The Jerusalem artichoke chips and mashed Jerusalem artichokes were tested for acceptability using the facial hedonic method with an untrained group of faculty or students at Kansas State University.

1. Method and Procedure

1.1 Sample preparation

Jerusalem artichoke chips were made by slicing unskinned Jerusalem artichoke tubers into chips with thickness of approximately one-eighth inch (0.3cm), and an approximate diameter of between one inch (2.5 cm) and one-third inch (0.8cm). These chips were deep fat fried at 140°C approximately for 15 minutes until the color became golden-brown. Sample A in Fig. 1

is the Jerusalem artichoke chips which were used as test sample, and sample B is the raw Jerusalem artichoke salads.

Mashed Jerusalem artichokes were created by boiling unpeeled Jerusalem artichoke tubers until they were soft. Then the skin was peeled, the tubers were mashed, and cream sauce and salt were added. Sample A in Fig. 2 is the mashed Jerusalem artichokes which were used as a test sample, and sample B is the egg salad with Jerusalem artichoke.

1.2 Facial hedonic method

The modified hedonic method, specifically, the facial hedonic method described below was used in this work to measure consumer acceptance (Peryam, 1957; Ellis, 1966).

In this method faces rather than scores and descriptions are employed. Fig. 3 shows the questionnaire used in the method. It provides for the rating of two samples at a session. The number of faces is generally five and the faces show no connotation of male or female characteristics. Each face has its own score, the least acceptable being one and the most acceptable being five. This has been successfully used by several large companies as reported by Ellis (1964). The method is simple and easily understood by test participants regardless of their individual intelligence level, education or ability to communicate. Also, the method encourages the taster to report his immediate naive response without any conscious effort to remember or to judge.

1.3 Tasting and tasters

Ideally a consumer test should cover a large sample of the population;



A B

Fig. 1. Jerusalem Artichoke Chips and Raw Jerusalem Artichoke Salads.



A B

Fig. 2. Mashed Jerusalem Artichoke and Egg Salad with Jerusalem Artichoke.

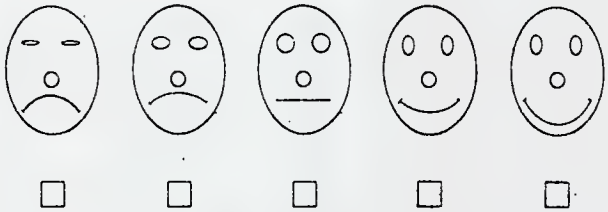
J. SAMPLE QUESTIONNAIRE: FACIAL HEDONIC METHOD

Sample #1

Name_____

ACCEPTANCE QUESTIONNAIRE

Date_____



Please check the box under the figure which best describes how you feel about this product.

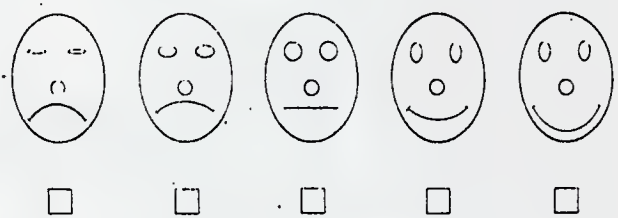
J. SAMPLE QUESTIONNAIRE: FACIAL HEDONIC METHOD

Sample #2

Name_____

ACCEPTANCE QUESTIONNAIRE

Date_____



Please check the box under the figure which best describes how you feel about this product.

Fig. 3. Questionnaire Used to Judge Specific Food Acceptance with the Facial Hedonic Method.

however, the number of people required for a given test cannot be arbitrarily stated. It depends on the importance of the problem and the degree of precision desired in the results (Kranerm 1963). The number of taste testers was 60 in this work. None of the tasters were trained panelists as stated previously.

The Jerusalem artichoke chips were served as sample #1 which was served first. Mashed Jerusalem artichokes were then served as sample #2. Each taster was asked to mark the box under the face which best describes how he or she felt about the test sample. Every effort was made to perform all the tests under exactly the same conditions. No attempt was made to give any information about the test to the panelists, since any information might influence the results.

2. Method of Data Analysis

In evaluating the results, a score was assigned to each face in Fig. 3, the face on the left receiving a rating of one and the face on the right receiving a rating of five. Numerical distributions thus obtained were treated statistically (Peryam, 1952). The means, standard deviations, standard errors of the means, and significance of differences between means were calculated.

RESULTS AND DISCUSSION

The distributions of responses for both Jerusalem artichoke chips and mashed Jerusalem artichokes are shown in Table 1 along with the result of the statistical treatment. It can be seen that the

Table 1. Distributions of Responses on Facial Hedonic Scale with Resulting Statistical Indices for Jerusalem Artichoke Chips and Mashed Jerusalem Artichoke

Scale description		Assigned value	Frequency of Responses	
			Jerusalem artichoke chips	Mashed Jerusalem artichoke
Like	extremely	5	20	18
Like	slightly	4	32	19
Neither like	no dislike	3	5	18
Dislike	slightly	2	3	3
Dislike	extremely	1	0	2
1. Total responses			60	60
2. Mean rating			4.15	3.80
3. Standard deviation			0.78	1.04
4. Varience of the mean			0.010	0.018
5. Percentage "Dislike" responses			5.0	13.3

mean ratings of sample #1 and #2 are 4.15 and 3.80, respectively. This implies that both of them would be considered acceptable under any circumstances; sample #1 appears to be more acceptable than sample #2, i.e., Jerusalem artichoke chips are more acceptable than mashed Jerusalem artichokes. The percentage of "dislike" responses for Jerusalem artichoke chips is only 5% for 60 people, and 13.3% for mashed Jerusalem artichokes.

Two possible reasons for the higher acceptability of Jerusalem artichoke chips is that the chips had a sweet taste resulting from a high content of fructose after frying and the earthy flavor prevailing in the mashed Jerusalem artichokes was probably eliminated or obscurred by deep fat frying.

CONCLUSION

It has been shown that the Jerusalem artichoke with two serving styles, Jerusalem artichoke chips and mashed Jerusalem artichokes, are highly acceptable and Jerusalem artichoke chips are more acceptable than mashed Jerusalem artichokes. These two serving styles are easy to prepare; therefore, Jerusalem artichoke is highly recommended as a table food.

The use of Jerusalem artichoke as a table food is widely known but insignificant in this country. The nutritive value of Jerusalem artichoke has not been definitely determined. Since its sugar content is starch-free, and it is non-diabetic. This fact has long been known (Weick, 1943). It can be cooked in every way a potato can; therefore, it is an ideal substitute for the starchy potato to diabetics.

As a table food, there are some handicaps for Jerusalem artichoke, the knobby, irregular appearance of tubers makes it not only unattractive but also inconvenient for cooking. The present breeding improvement techniques will solve this problem. In the U.S., the high price of Jerusalem artichoke also prevents its development. It seems that if given a fair opportunity this native American vegetable will prove its worth in many American gardens and solve the problem of food shortages.

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CHAPTER 9

CONCLUSIONS AND RECOMMENDATION

The feasibility of Jerusalem artichoke as as source of food and energy has been investigated in this study. The literature survey has indicated that the Jerusalem artichoke is an efficient solar crop that is easy to grow; it is a potential source for food and energy.

Several significant conclusions have been drawn from the experimental phase of this investigation.

(1) Among three sample preparation methods for extraction polysaccharides for eventual production of reducing sugar, i.e., grinding, slicing, and cubing, slicing gives the highest yield.

(2) The combination of an extraction temperature of 80°C and an extraction time of one hour gave in the maximum yield of reducing sugar from Jerusalem artichoke tubers.

(3) The most favorable condition for conversion of polysaccharides in the Jerusalem artichoke extract to reducing sugar was found at a pH of 1.5, a temperature of 80°C, and a reaction time of 30 minutes.

(4) The hydrolysis of inulin to fructose is a first-order reaction and its activation energy is 13442.1 calories/g-mole.

(5) The Jerusalem artichoke tubers possess a high potential as a raw material for the production of alcohol. Unclarified-unhydrolyzed extract of Jerusalem artichoke tubers gives a higher yield of alcohol than clarified-hydrolyzed extract.

(6) The batch anaerobic digestion of Jerusalem artichoke tubers for producing methane gas is technically feasible, and at least 0.8 cu. ft. of gas can be produced from 135 grams (dry weight) of tubers.

(7) Jerusalem artichoke tubers as a table food in the style of either fried Jerusalem artichoke chips or mashed Jerusalem artichoke are highly acceptable.

Fructose obtained from the hydrolysis of Jerusalem artichoke extract can probably be concentrated and precipitated by a newly proposed method. This involves uses of hyperfiltration and cryogenic cooling (Fan, 1976). It appears that methane production from Jerusalem artichoke tubers can be carried out in a fluidized bed, fixed bed or semifluidized bed bioreactor (Fan, 1978). Besides the utilizations of Jerusalem artichoke tubers as raw material for the productions of fructose, alcohol, methane, and as food, the leaves and stalks of the Jerusalem artichoke can be used as feed directly or converted into alcohol, substitute fuel and synthesis gas by various means. Even cellulosic wastes from the processing of Jerusalem artichoke tubers can be used for the same purposes. Means suggested in the literature for converting Jerusalem artichoke leaves, stems, and wastes into alcohol, substitute fuel, and synthesis gas include enzymatic or acidic hydrolysis followed by fermentation, pyrolysis followed by catalytic synthesis, and others. These areas need further investigation.

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APPENDIX 1.

ANALYSIS OF KINETICS OF INULIN TO FRUCTOSE

The experimental data at temperatures of 50°, 60°, 65°, 70°, and 75°C were extrapolated to their fictitious initial points (t=0) where the concentrations of reducing sugar would have been zero. All the experimental data were adjusted to the fictitious initial points. The conversion data are shown in Tables A-1 through A-5 and are plotted in Fig. A-1, the slopes of which are the values of k. The standard errors of these least square line ranging from 0.061 to 0.249. The values of k are summarized in Table A-6. A semilogarithmic plot of k as a function of $\frac{1}{T}$ is shown in Fig. A-2, the slope of which is $(-\frac{E}{R})$ and the standard error of this least square line is 0.148. The activation energy E was recovered from it as 13,442.1 calories/g-mole.

Table A-1. Experimental Conversion Data of Inulin to Fructose at 50°C

Time (min.)	Adjusted time (min.)	Cr		$C_{r\infty} - C_r$ (M)	$\frac{C_{r\infty} - C_r}{C_{r\infty}}$	$\ln(\frac{C_{r\infty} - C_r}{C_{r\infty}})$
		(g_0)	(M)			
10	30.03	2.40	0.0133	0.0506	0.7913	- 0.2341
20	40.03	2.75	0.0153	0.0486	0.7609	- 0.2733
30	50.03	3.20	0.0178	0.0461	0.7217	- 0.3261
60	80.03	4.45	0.0247	0.0392	0.6130	- 0.4893
90	110.03	5.77	0.0321	0.0318	0.4983	- 0.6966
150	170.03	7.89	0.0438	0.0201	0.3139	- 1.1586
∞	∞	11.50	0.0639	0.0000	0.0000	$-\infty$

Note:

1. C_r = Concentration of reducing sugar at any time
2. $C_{r\infty}$ = Concentration of reducing sugar at time of infinity
3. C_{r0} = Concentration of reducing sugar at time zero
4. M = Molarity

Table A-2. Experimental Conversion Data of Inulin to Fructose at 60°C

Time (min.)	Adjusted time (min.)	Cr		$C_{r\infty} - C_r$ (M)	$\frac{C_{r\infty} - C_r}{C_{r\infty}}$	$\ln(\frac{C_{r\infty} - C_r}{C_{r\infty}})$
		(g_0)	(M)			
10	19.56	3.28	0.0182	0.0640	0.7784	- 0.2505
20	29.56	4.77	0.0265	0.0557	0.6777	- 0.3891
30	39.56	6.10	0.0339	0.0483	0.5878	- 0.5313
60	69.56	9.03	0.0502	0.0320	0.3899	- 0.9420
90	99.56	10.85	0.0603	0.0219	0.2669	- 1.3209
150	159.56	13.02	0.0723	0.0099	0.1203	- 2.1180
∞	∞	14.80	0.0822	0.0000	0.0000	- ∞

Note:

1. C_r = Concentration of reducing sugar at any time.
2. $C_{r\infty}$ = Concentration of reducing sugar at time of infinity
3. C_{r0} = Concentration of reducing sugar at time of zero
4. M = Molarity

Table A-3. Experimental Conversion Data of Inulin to Fructose at 65°C

Time (min.)	Adjusted time (min.)	Cr		$C_{r\infty} - C_r$ (M)	$\frac{C_{r\infty} - C_r}{C_{r\infty}}$	$\ln(\frac{C_{r\infty} - C_r}{C_{r\infty}})$
		(g_0)	(M)			
10	25.37	4.77	0.0265	0.0599	0.6934	- 0.3661
20	35.37	6.93	0.0385	0.0479	0.5546	- 0.5895
30	45.37	8.60	0.0478	0.0386	0.4473	- 0.8045
60	75.37	11.88	0.0660	0.0204	0.2365	- 1.4418
90	105.37	13.17	0.0732	0.0132	0.1536	- 1.8734
150	165.37	14.63	0.0813	0.0051	0.0598	- 2.8167
∞	∞	15.56	0.0864	0.0000	0.0000	- ∞

Note:

1. C_r = Concentration of reducing sugar at any time
2. $C_{r\infty}$ = Concentration of reducing sugar at time of infinity
3. C_{r0} = Concentration of reducing sugar at time of zero
4. M = Molarity

Table A-4. Experimental Conversion Data of Inulin to Fructose at 70°C

Time (min.)	Adjusted time (min.)	Cr		$C_r - C_r$ (M)	$\frac{C_r - C_r}{C_r}$	$\ln(\frac{C_r - C_r}{C_r})$
		(g_0)	(M)			
10	38.27	6.67	0.0371	0.0523	0.5857	- 0.5349
20	48.27	9.54	0.0530	0.0364	0.4075	- 0.8978
30	58.27	11.71	0.0651	0.0243	0.2727	- 1.2995
60	88.27	14.20	0.0789	0.0105	0.1180	- 2.1370
90	118.27	14.80	0.0822	0.0072	0.0807	- 2.5165
150	178.27	15.60	0.0867	0.0027	0.0311	- 3.4720
∞	∞	16.10	0.0894	0.0000	0.0000	- ∞

Note:

1. C_r = Concentration of reducing sugar at any time.
2. $C_{r\infty}$ = Concentration of reducing sugar at time of infinity
3. C_{r0} = Concentration of reducing sugar at time of zero
4. M = Molarity

Table A-5. Experimental Conversion Data of Inulin to Fructose at 75°C

Time (min.)	Adjusted time (min.)	Cr		$C_{r\infty} - C_r$ (M)	$\frac{C_{r\infty} - C_r}{C_{r\infty}}$	$\ell n(\frac{C_{r\infty} - C_r}{C_{r\infty}})$
		(g_0)	(M)			
10	35.26	9.18	0.0510	0.871	0.4450	- 0.8097
20	45.26	12.64	0.0702	0.8518	0.2386	- 1.4330
30	55.26	14.20	0.0789	0.8431	0.1446	- 1.9338
60	85.26	15.77	0.0876	0.8344	0.0500	- 2.9957
90	115.26	16.20	0.0900	0.8320	0.0241	- 3.7255
150	175.26	16.53	0.9180	0.0040	0.0042	- 5.4729
∞	∞	16.63	0.9220	0.0000	0.0000	- ∞

Note:

1. C_r = Concentration of reducing sugar at any time
2. $C_{r\infty}$ = Concentration of reducing sugar at time of inifinity
3. C_{r0} = Concentration of reducing sugar at time of zero
4. M = Molarity

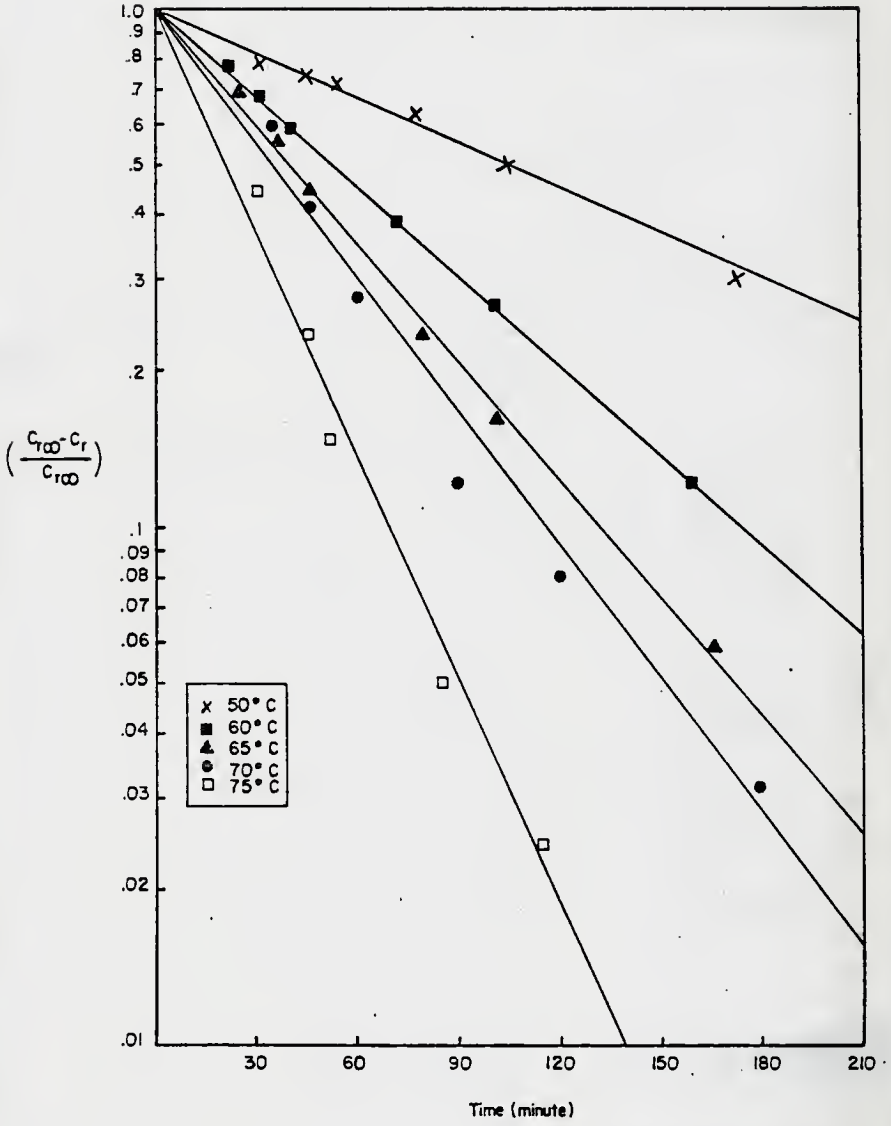


Fig. A-1. Fractional Unconverted Inulin Concentration vs Time.

Table A-6. The Hydrolysis $(C_6H_{10}O_5)_m \cdot H_2O + H_2O \longrightarrow m\ C_6H_{12}O_6$

Temp. (°K)	$1/T^*$ ($°K^{-1}$)	k^{**} (min^{-1})	ℓn k
323	3.096×10^{-3}	0.0066	- 5.0207
333	3.003×10^{-3}	0.0133	- 4.3200
338	2.959×10^{-3}	0.0175	- 4.0456
343	2.915×10^{-3}	0.0205	- 3.8873
348	2.873×10^{-3}	0.0320	- 3.4420

* T is the absolute temperature

** k is the rate constant at a given temperature

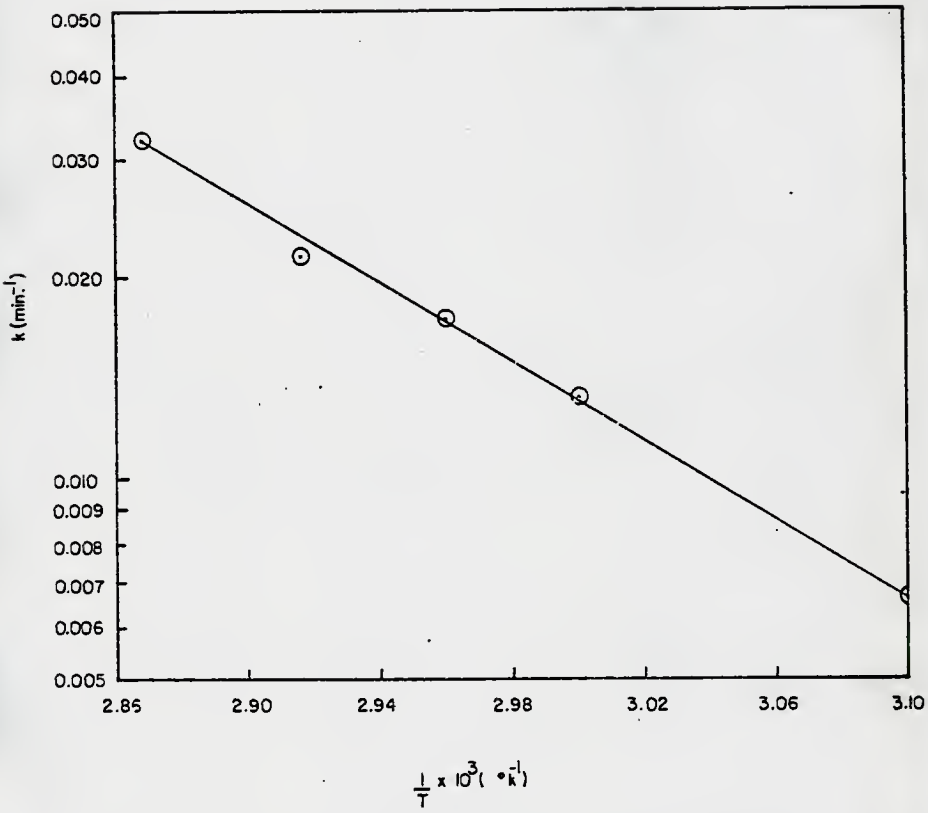


Fig. A-2. Arrehenius Plot of the Hydrolysis $(C_6H_{10}O_5)_m \cdot H_2O \longrightarrow mC_6H_{12}O_6$.

JERUSALEM ARTICHOKE —— A Potential Solar Crop for Food and Energy Supplies

by

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Taiwan, 1973

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

FOOD SCIENCE

Department of Chemical Engineering

Kansas State University

Manhattan, Kansas

1978

ABSTRACT

The objectives of this research were to investigate the conversion of Jerusalem artichoke to fructose by extraction and hydrolysis, to evaluate the technical feasibility of using Jerusalem Artichoke in alcohol production by fermentation and methane production by anaerobic digestion, and to study the acceptibility of Jerusalem artichoke as a food. An exhaustive review of the literature has revealed that the Jerusalem artichoke, a native North American plant that provides solar energy fixation in the form of inulin (a polyfructosan), is a good source of food and energy.

The Jerusalem artichoke was found to be productive and very easy to grow. The optimum conditons for the extraction of polysaccharides (mainly inulin) from Jerusalem artichoke tubers corresponded to a temperature - time combination of 80°C and 1 hour. The optimum conditions for conversion of polysaccharides (inulin) from Jerusalem artichoke tubers to reducing sugar (mainly fructose) were a treatment time of 30 minutes, a temperature of 80°C, and a pH of 1.5. The hydrolysis of inulin to fructose was found to be a first - order reaction and to have an activation energy of 13442 calories/g-mole. It was experimentally determined that Jerusalem artichoke tubers possess a high potential as a raw material for the production of alcohol. The batch anaerobic digestion of Jerusalem artichoke tubers for producing methane was found to be technically feasible. It was determined that the serving of Jerusalem artichoke tubers as a table food in the style of either Jerusalem artichoke chips or mashed Jerusalem artichoke is highly acceptable.

Besides the utilizations of Jerusalem artichoke tubers as raw

materials for the productions of fructose, alcohol, methane and as food, the leaves and stalks of the Jerusalem artichoke can probably be used as feed directly or converted into alcohol, substitute fuel and synthesis gas by various means.